2020

SSERVI ANNUAL REPORT

SSERVI
2020 ANNUAL REPORT

SOLAR SYSTEM EXPLORATION RESEARCH

VIRTUAL INSTITUTE

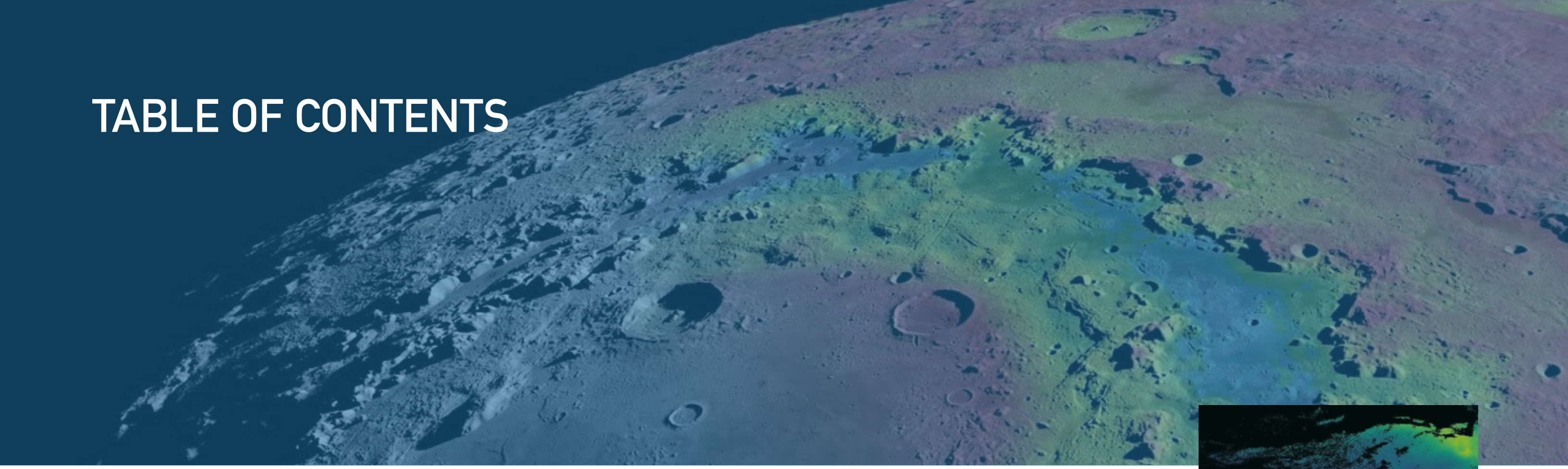
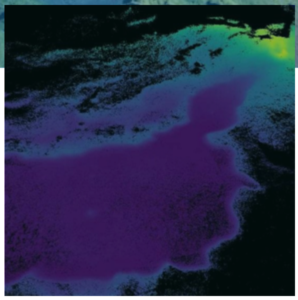
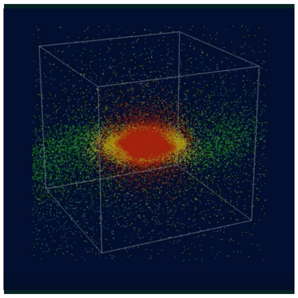
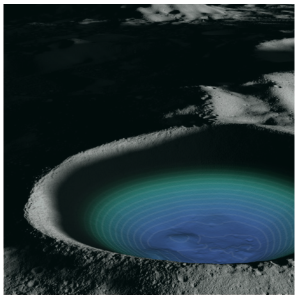
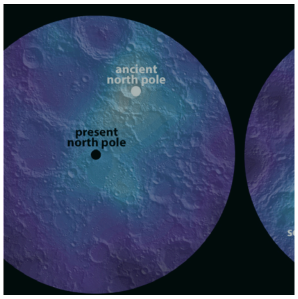


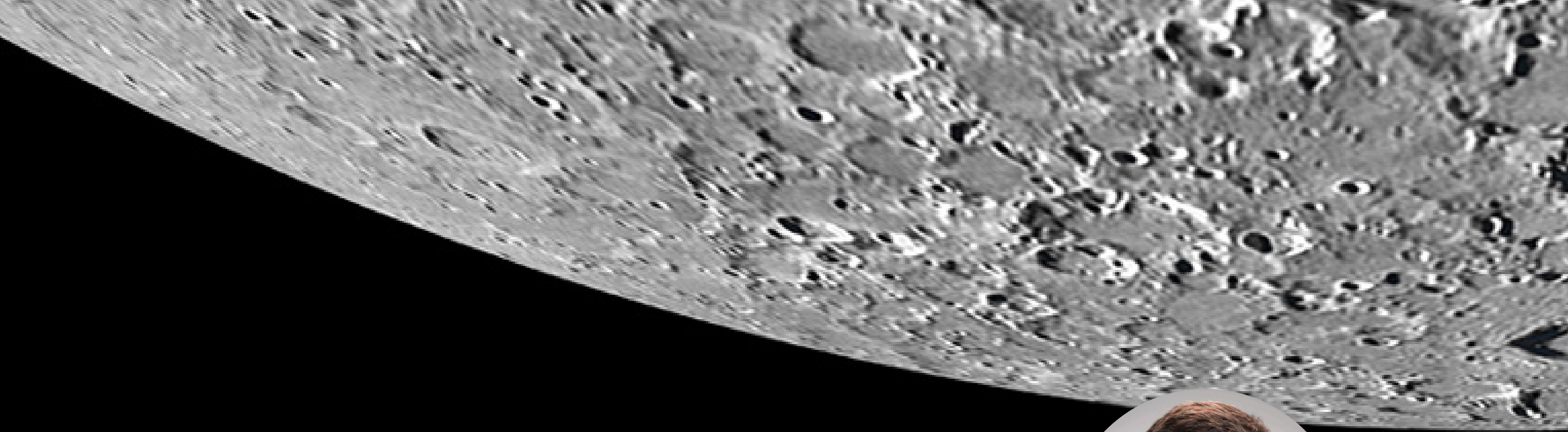
TABLE OF CONTENTS











FROM THE BRIDGE

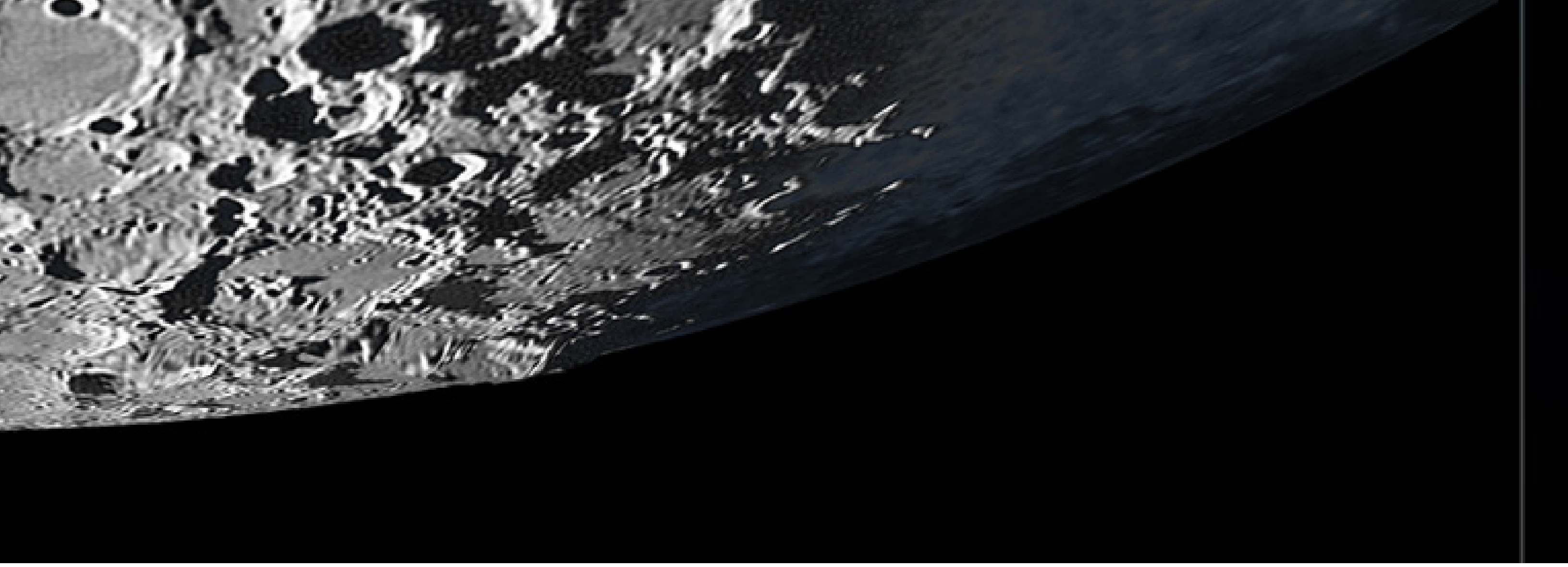
Dear Exploration Science community,

2020 was one of the most challenging years in our nation's history, and in each of our lives. The COVID-19 pandemic and its fallout affected both our country and every one of us, through the staggering losses we have suffered and other major impacts to all of our lives. Deep racial injustice forced the nation and many institutions to realize and confront the systemic racism endured by so many. Families, without the support of child care and many working from home, have endured major hardships of their own, with a disproportionate impact on women.

Despite these profound challenges, SSERVI has developed creative solutions at all levels to allow our institute to thrive and continue its important work contributing to NASA's science and human exploration enterprises. Indeed, forcing the institute to operate remotely most of the year played to SSERVI's strengths in many ways, allowing us to contribute to the community immediately after the pandemic hit. There were major impacts, certainly – the inability to do laboratory work for much of the year, and the need to postpone important field work, impacted the plans of nearly all of the institute's scientists. The sudden closure of NASA Ames, the first NASA center to close during the pandemic, hit close to home and like so many others, made the daily personal interactions we had taken for granted a rarity. But the opportunity to help both the institute itself and the broader community through our expertise in virtual institute operations was one that SSERVI rose to through events ranging from the European Lunar Symposium to numerous Lunar Surface Science Workshops, along with many others.

SSERVI began to address systemic racism through a clear statement sent via social media and its website [https://sservi.nasa.gov/articles/15083/], as well as the formation of a Focus Group to examine issues in Equity, Diversity and Inclusion. This group has made progress quickly towards one of its major goals of coming up with a response and plan to address pervasive inequality. These issues have become part of the fabric of SSERVI and are providing impetus for positive change in the institute.

Given these dynamic times, this 2020 Annual Report highlights not only what we did, but how we're moving forward. Whether you were on Zoom, WebEx, MS Teams, or FaceTime, this kind of virtual connection is here to stay. For years SSERVI has pressed the leading edge of virtual collaboration technology in order to connect its domestic teams and international partners, and as noted, this year we also supported the larger community and agency in producing a variety of virtual conferences, webinars, workshops, seminar series, and meetings which are subsequently detailed in



this report. SSERVI has been both pleased and honored to receive positive feedback from the community on both its implementation of now-standard platforms as well as its novel approaches, such as the NESF virtual poster session. SSERVI's objectives have been clear – continue to highlight the high-quality research done by the institute and the community, while connecting the community in the best possible ways, in a time when personal connections have been difficult or impossible. And with the disproportionate impact felt by the next generation during the pandemic, SSERVI has focused a great deal of effort on providing opportunities for this key segment of the community.

Bridging science with human exploration efforts has become even more important as we prepare to return humans to the Moon and then on to Mars, and SSERVI is continuing to find opportunities to incorporate its science into the Artemis critical path. The opportunities for science through Artemis and NASA's new robotic lunar program are immense, and SSERVI is proud to be playing a critical role in this agency endeavor. Furthermore, bringing commercial and international attention to a wide variety of research efforts has and will continue to be a prime focus for SSERVI.

Since its inception, SSERVI has been proud to advance transformative lunar and small body science by advancing the state-of-the-art of exploration science, and connecting its teams and partners around the globe. Along with all of you, we have withstood this very difficult year. But our commitment to helping humanity achieve its grand goals of exploring our solar system hasn't wavered. As we look to the past, we are keeping an eye on the future, excited for the many upcoming missions and new discoveries that await. We are proud to present this 2020 SSERVI Annual Report.

Ad astra,

Gregory Schmidt
SSERVI Director

SSERVI.NASA.GOV

twitter.com/NASA_Lunar

SSERVI Central Office

As a virtual institute, SSERVI funds a range of U.S. teams and facilitates collaboration among teams, as well as commercial and international partners, to advance science and exploration. The SSERVI Central Office exercises overall leadership of the institute, setting strategic direction and managing domestic teams. It promotes the institute's research to NASA Headquarters and the planetary science and exploration communities. The SSERVI Central Office also supports the planetary science community, with a strong focus on the next generation and diversity, and actively advances Information Technology adoption and production for better virtual collaboration.

In support of these objectives, SSERVI Central has a team with a broad set of expertise that includes:

- Administration/Management
- Lunar & Planetary Science
- Data Visualization
- Partnerships
- Scientific & Technical Writing
- Facility Management
- Executive Administrative Support
- Training
- Public Engagement
- Virtual Collaboration Production
- Web Development
- Content Development / Graphic Design

PROMOTE
Science Exploration Support for SSERVI & Community

Administration for 12 P.I. Teams
Research Solicitation, Selection & Management
Collaboration Facilitation Through Executive Council & Site Visits
Focus Groups
Exploration Initiatives and Support
Advocacy & Reporting w/ SMD, HEOMD, & STMD
Strategic Vision / White Papers
Science Dissemination
NASA Exploration Science Forum / Focused Workshops
LEAG & SBAG Support
ELS / Pan-European Collaboration
Inclusion, Diversity, Equity, and Accessibility Initiatives
Mission Support (e.g. RP, ISEEE, LOIRP, ALSEP)
International Partnerships
Commercial Engagement
Solar System Treks Program Management
Regolith Testbed Facilities Management
Professional Research Travel Support

TRAIN
Next Gen Support

NASA Postdoctoral Program
Lunar and Small Bodies Graduate Conference (LunGradCon)
Next Generation Lunar Scientists and Engineers (NGLSE) Support
Student Internships and Analog Field Opportunities
Student Exchange / Travel
Teacher Training
Robotics Competition Support (Judging, Speaking)

INSPIRE
Public Engagement

Lead Coordination of SSERVI Team Public Engagement Working Group
Support and Advocacy for Fireballs in the Sky & Global Fireball Network Expansion
Student Engagement (K-Undergraduate)
Journey Through the Universe Support (Native Islander Program)
Student Science Clubs
Braille Books (Accessibility)
Special Event Support (e.g. 2017 Eclipse, InSight Launch, International Observe the Moon Night)
Public Engagement via Website & Social Media

CONNECT
Collaborative Technology

Virtual Event Production for SSERVI Events & Teams
Exploration Science Forum
SSERVI Workshops Without Walls
Community Workshops (e.g. SBAG)
NASA HQ (SMD & HEO) (e.g. GER, NESSF Reviews, LSSW)
SSERVI Team Seminar Series
SSERVI & Community Website Development & Management
NASA IT Security Plan & Management
New Collaborative Technology Testing & Implementation
Silicon Valley Partnerships

SSERVI Central Staffing Updates

Kristina Gibbs, SSERVI Deputy Director

Kristina Gibbs became SSERVI Deputy Director in 2020. Prior to being selected as Deputy Direct, Kristina was the SSERVI Associate Director since 2016. Before joining SSERVI, she supported space life sciences payloads and was a contractor department head and manager for virtual institutes, education and technology programs. In addition, Kristina managed several highly successful summer student research programs, including NASA Ames Academy programs and the Space Life Sciences Training Program. Kristina started her career supporting space life science flight payloads on the Mir Space Station, Space Shuttle, and the International Space Station. She has developed a diverse experience base which includes project management of spaceflight research payloads, education and public outreach projects, international collaborations, hardware development, and fostering innovative partnerships with NASA. Kristina brings extensive experience leading multi-disciplinary teams and facilitating communication across scientific, technical, and administrative organizations. Kristina is a recipient of the Space Flight Awareness Award, the "Silver Snoopy," as well as several NASA Ames and contractor management achievement awards. She holds a B.S. in Molecular and Cellular Biology from the University of Arizona.

Carle Pieters, SSERVI Distinguished Scientist

In 2020 Carle Pieters assumed the role of SSERVI Distinguished Scientist, a prestigious position formerly held by Nobel laureate Barry Blumberg. Pieters will advise the agency and lend her expertise in lunar exploration to SSERVI science and the ambitious goals of Artemis program objectives. Pieters earned her B.A. from Antioch College, and her B.S., M.S. and Ph.D. in Planetary Science from the Massachusetts Institute of Technology. Dr. Pieters spent three years at NASA Johnson Space Center before her career as a professor at Brown University. She was Principal Investigator for the Moon Mineralogy Mapper (a guest instrument on the Indian Chandrayaan-1 spacecraft) which characterized the mineralogy of the Moon on a global scale. She has recently served as a Co-Investigator on NASA's Dawn mission to the asteroids Vesta and Ceres and is currently a Co-Investigator on Trailblazer, a NASA SIMPLEX mission to explore the lunar water cycle. She has been elected a Fellow of the American Association for the Advancement of Science, American Geophysical Union, Geological Society of America, and Meteoritical Society. In 2020 she was elected a Legacy Fellow of the American Astronomical Society. Asteroid 3713 Pieters was named after her. Pieters has been honored with several significant awards, including the AAS/DPS Kuiper Prize (2004), the GSA GK Gilbert Award (2010), NASA Exceptional Scientific Achievement Medal (2010), and the COSPAR International Cooperation Medal (2014). In 2015, SSERVI awarded her the 2015 Shoemaker Distinguished Scientist Medal for lifetime dedication and impact to the planetary science research community.

Exploration Science enables human exploration or results from it. The guiding principle is **science enables exploration, exploration enables science[1].**

The Solar System Exploration Research Virtual Institute (SSERVI)

is a Virtual Institute at the intersection of science and exploration. It is comprised of a global network of dispersed, interdisciplinary researchers collaborating to address key fundamental science and human exploration questions. The scope of SSERVI research includes NASA's top destinations for human explorers, including NASA's bold plan to go forward to the Moon and beyond through the Artemis Program.

1.This phrase was first developed by Mark Robinson, P.I. for LROC, and popularized by Mike Wargo, former NASA ESMD Chief Scientist.

PROMOTE

Artist's concept MMX Spacecraft. Photo credit: JAXA

At the core of SSERVI is the objective to promote planetary science and exploration, and to exchange knowledge among these communities to further advance human and robotic exploration of the solar system. SSERVI supports SMD/HEO goals in resolving key knowledge gaps that are critical to the agency's mission, and forges partnerships with international organizations and commercial entities who can contribute specific expertise.

SSERVI funds science and exploration research that addresses complex, multi-faceted questions. Interdisciplinary research teams are funded for 5 years, which allows for flexibility to changing NASA needs, as well as allowing research teams to pursue new lines of scientific discovery and follow key science leads. Often, this kind of interdisciplinary research would be difficult or would not have been achieved in the absence of this funding model. SSERVI also provides secure, long-term funding for graduate students and postdoctoral positions. As new questions and results arise, SSERVI can respond to NASA HQ with targeted expertise within SSERVI to answer NASA's questions pertinent to exploration science and to provide critical help to Artemis, VIPER and other agency priorities.

SSERVI has made sustained contributions to the planetary science community and NASA's lunar exploration efforts for well over a decade now (including under its previous name, the NASA Lunar Science Institute). It has led in the advancement of transformative lunar science, and has developed mission, instrument and technology concepts specifically related to exploration science, and has contributed to mission planning and operations through SSERVI's Solar System Treks Portal and innovative AR/VR display systems. SSERVI has developed and continues to promote a wide array of cutting-edge facilities, available not only to SSERVI researchers but also to the broader community. These include a Regolith Testbed and Lunar lab, with over eight tons of lunar regolith simulant, and the world's most powerful hypervelocity dust accelerator.

SSERVI also looks to strengthen the planetary science community by supporting conferences, workshops, analysis groups, and focus groups-- including a new Inclusion, Diversity, Equity, and Accessibility Initiative created to address key issues in science and exploration of the Moon and asteroids that are related to equity, ethics, diversity, inclusion, and social justice.

The following section highlights selected contributions from SSERVI in support of the Institute, planetary science community, and Agency mission objectives in 2020.

SSERVI PRINCIPAL INVESTIGATORS

Prof. Daniel Britt
Center for Lunar and Asteroid Surface Science (CLASS)
University of Central Florida, Orlando

Prof. Jack Burns
Network for Exploration and Space Science (NESS)
University of Colorado, Boulder

Dr. Jeffrey Gillis-Davis
Interdisciplinary Consortium for Evaluating Volatile Origins (ICE FIVE-0)
Washington University in St.Louis

Prof. Timothy Glotch
Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2)
Stony Brook University

Dr. Jennifer Heldmann
Resource Exploration and Science of OUR Cosmic Environment (RESOURCE)
NASA Ames Research Center

Dr. Amanda Hendrix
Toolbox for Research and Exploration (TREX)
Planetary Science Institute

Prof. Mihaly Horanyi
Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)
University of Colorado, Boulder

Dr. Rosemary Killen
Lunar Environment And Dynamics for Exploration Research (LEADER)
NASA Goddard Space Flight Center

Dr. David Kring
Center for Lunar Science and Exploration (CLSE)
Lunar and Planetary Institute

Prof. Thomas Orlando
Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)
Georgia Tech

Dr. Alex Parker
Exploration Science Pathfinder Research for Enhancing Solar System Observations (ESPRESSO)
Southwest Research Institute

Dr. Nicholas Schmerr
Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES)
University of Maryland

VIRTUAL SITE VISITS

Site visits to SSERVI Teams are coordinated at least once during each Team's 5-year research effort. These site visits are attended by SSERVI leadership and representatives from all of the other Teams, with the aim of both informing each of the Teams as well as creating cross-team research efforts. The visits provide opportunities to highlight ongoing research, showcase facilities and instrumentation development, and foster new cooperation in research or education. In 2020 the site visits were both virtual; despite the lack of valuable in-person interaction, this approach allowed a broader subset of the teams to participate, with a significantly higher number of online participants. The Team-led virtual presentations and laboratory tours successfully demonstrated the use of this approach, and virtual participation will undoubtedly be at least a part of future SSERVI Team site visits.

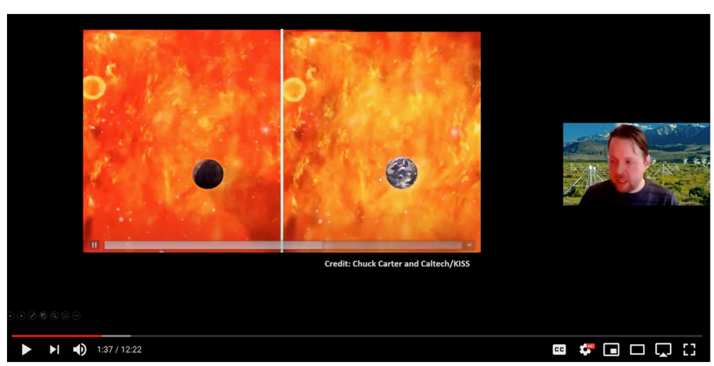
The TREX Site Visit on November 13, 2020, consisted of dynamic presentations, videos, and more! The robust agenda featured P.I. Amanda Hendrix and TREX team members detailing investigatory themes of a UV-MIR Spectral Library of Fine Particle Minerals+, the Moon, Small Bodies, Field Studies and Applications, and Outreach. Researchers detailed their work using LAMP to look at water across the lunar surface, cold traps and ice storage, and mapping minerals and water with rover tetracorders. The virtual site visit also included virtual tours of PSI, LASP, Winnipeg, and DLR laboratories. Discover all the archives posted at trex.psi.edu.

TREX Virtual Site Visit - Amanda Hendrix.

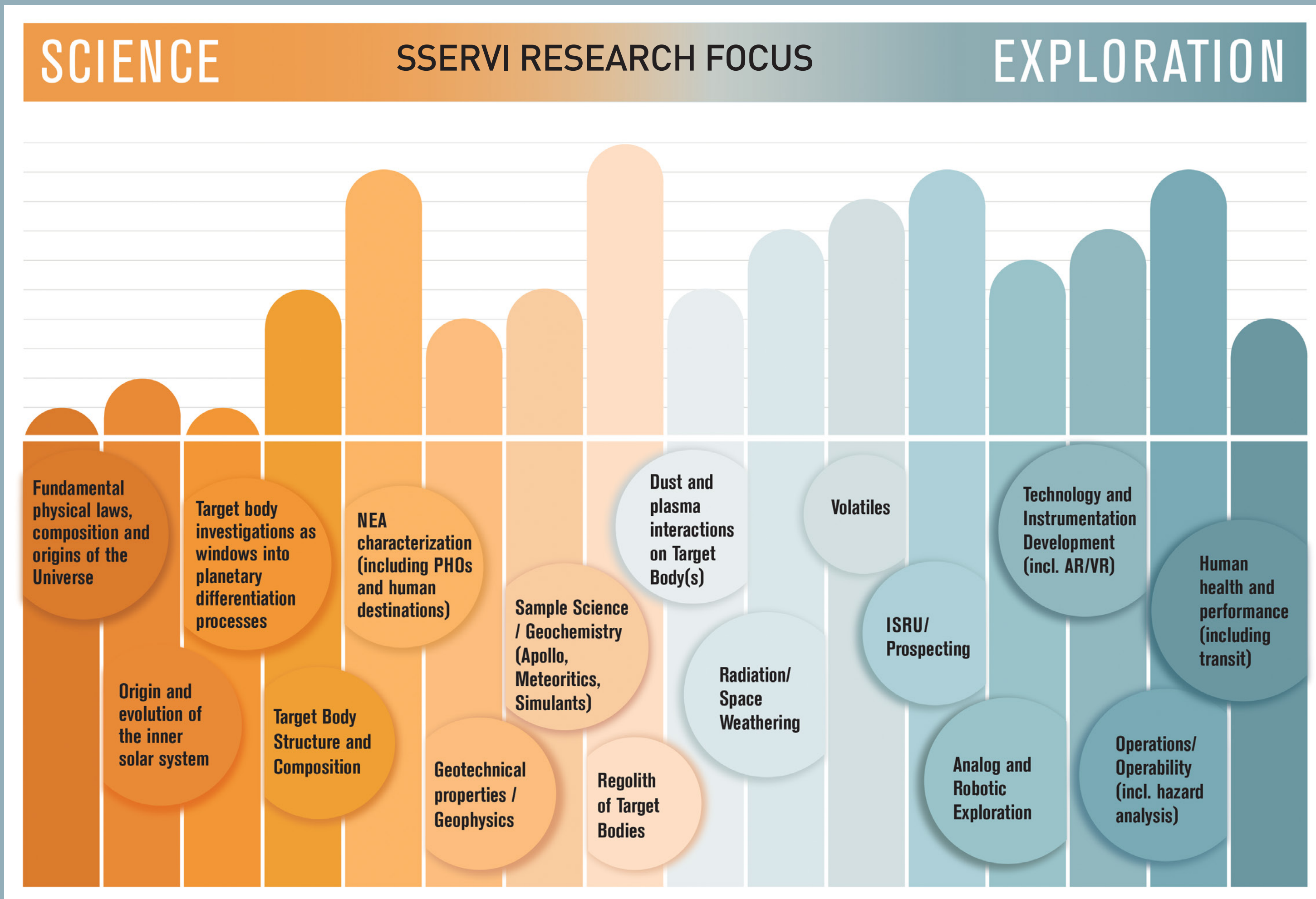
TREX Virtual Site Visit - PSI Senior Scientist Darby Dyar discusses sample preparation and characterization.

The NESS Site Visit on November 30, 2020, used Zoom to connect SSERVI researchers with the team's work on Heliophysics, Exoplanet Magnetospheres, the Global 21 cm Signal, Telerobotics, and Outreach. NESS P.I. Jack Burns and team members detailed several inspiring Missions and Mission concepts, including: SunRISE, ROLSES, FARSIDE, EDGES, Cosmic Twilight Polarimeter, and DAPPER. Researchers further detailed advanced concepts of operations using mixed reality interfaces for the teleoperation of lunar robots, along with robot deployment and supervision strategies. Outreach highlights included a personal screening of the planetarium show "Forward! To the Moon."

NESS Virtual Site Visit - Jack Burns introduction.

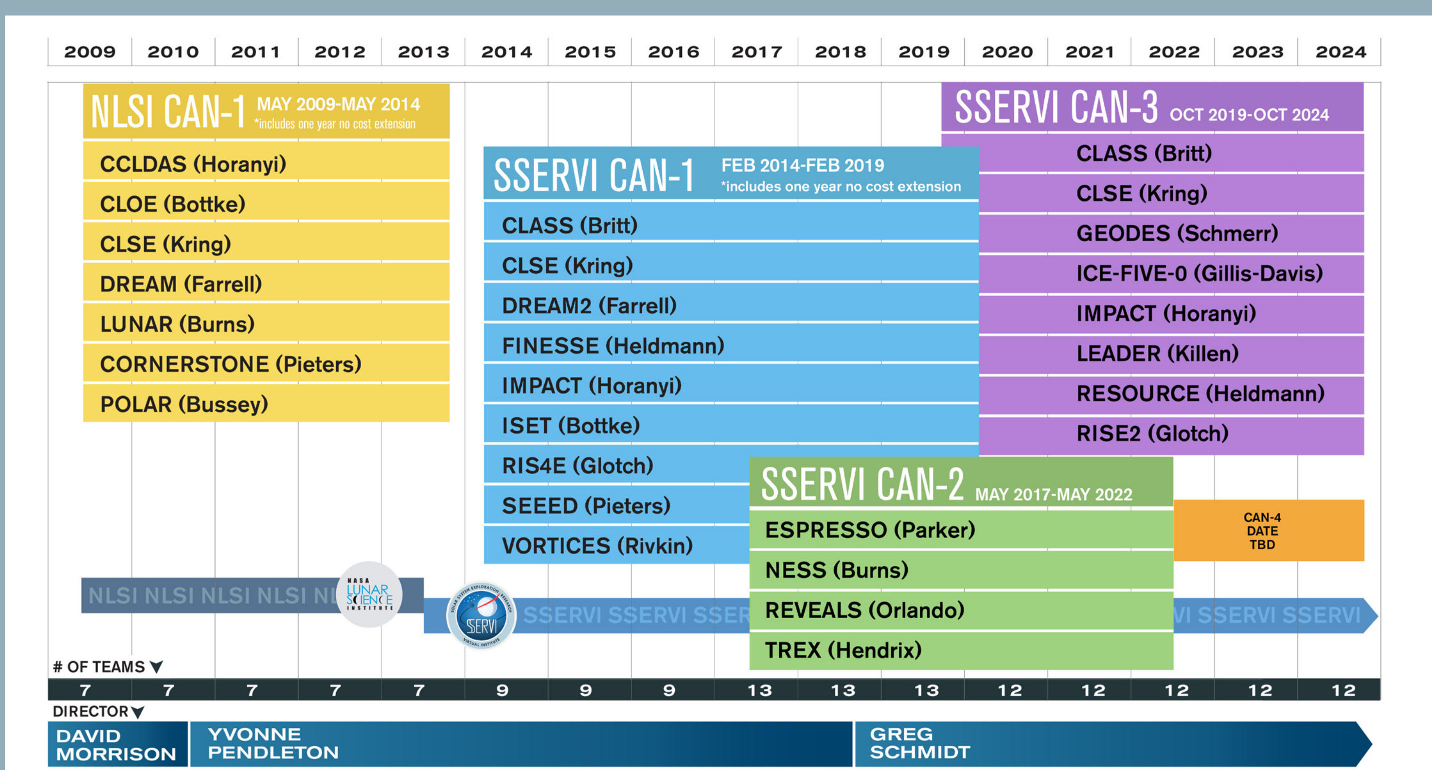


NESS Virtual Site Visit - Exoplanetary System Observations with FARSIDE Gregg Hallinan.

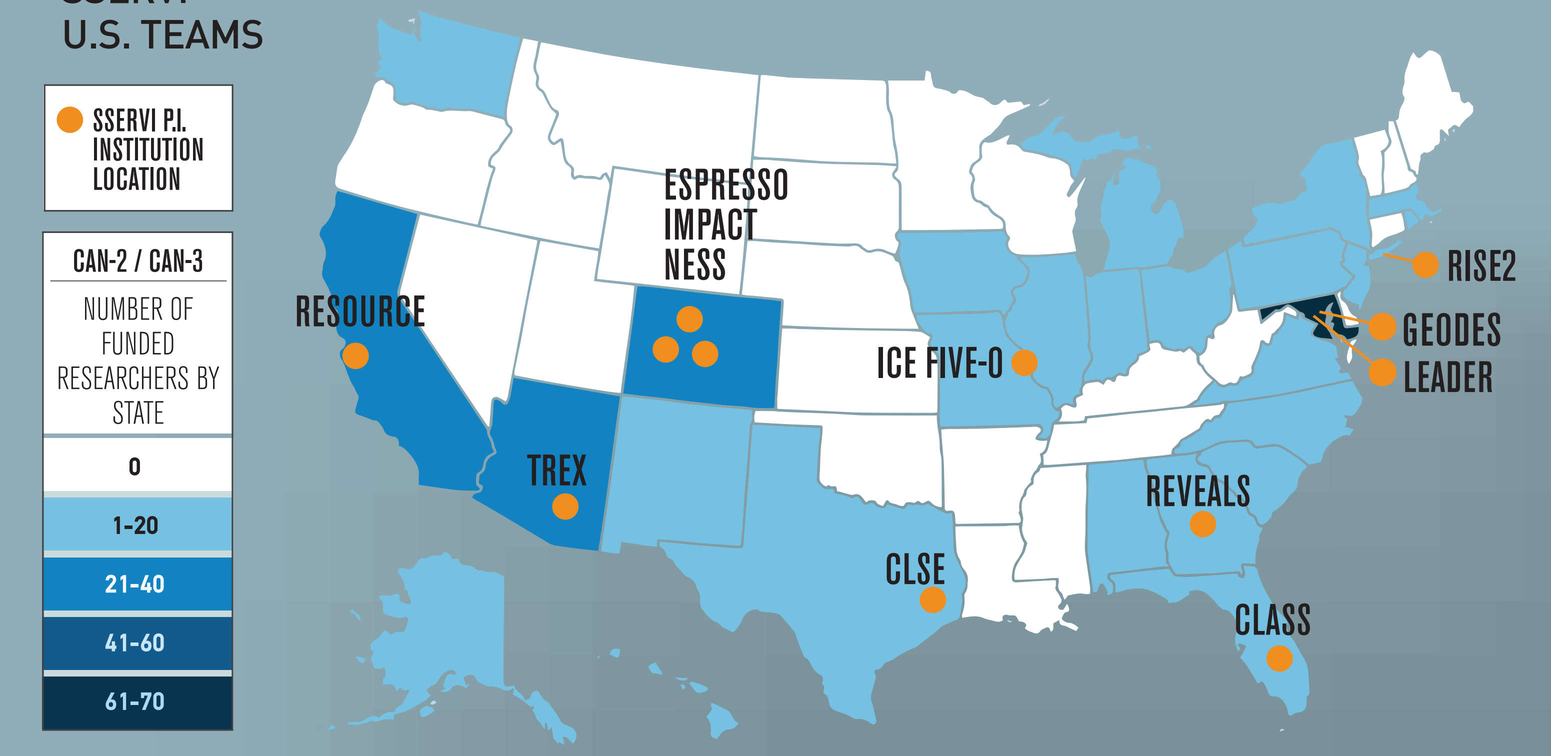


SSERVI research spans the spectrum of fundamental science to human exploration. This chart represents the research focus areas and the bar chart represents the number of SSERVI teams that are addressing a given research area as part of their proposed science.

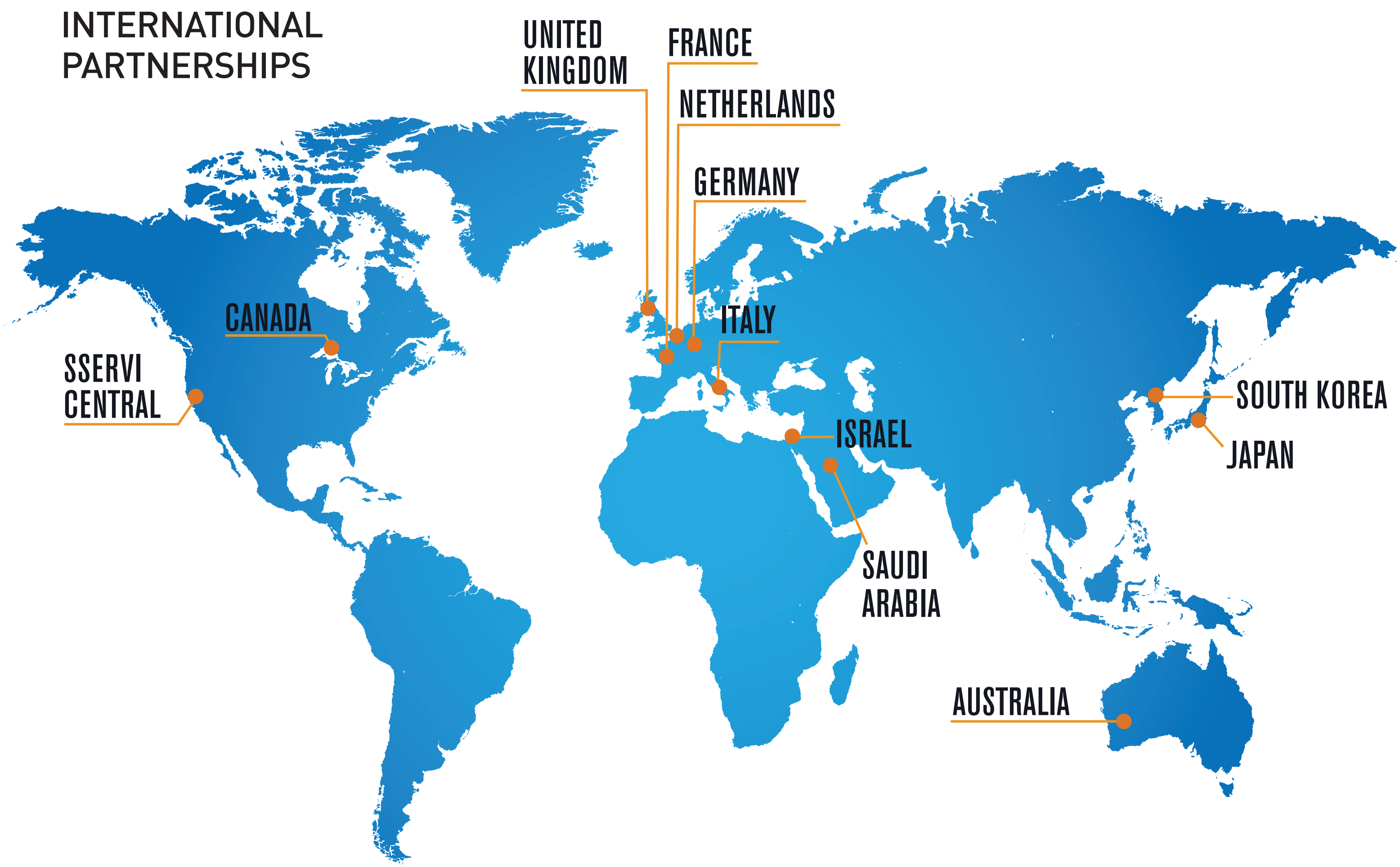
Starting with the NASA Lunar Science Institute (NLSI), SSERVI has awarded 5-year cooperative agreements to selected teams. This graphic shows the historical timing of all previous CANs, and identifies the timing for the planned SSERVI CAN-4.

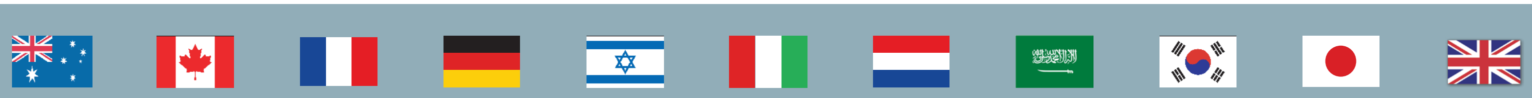


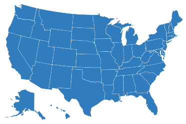
SSERVI U.S. TEAMS



SSERVI INTERNATIONAL PARTNERSHIPS







12 Domestic Teams — 23% FEMALE, 77% MALE

11 International Partners

CAN-2 + CAN-3 RESEARCHERS

457 Total Individual Team Members* (55 on multiple teams)

264 Individual Domestic Funded Researchers

139 Individual Domestic Collaborators (Unfunded)

54 International Collaborators (Unfunded)

*as proposed

SSERVI PUBLICATIONS
2014-2020

1038 SSERVI PEER REVIEWED PUBLICATIONS

22% student involved publication

17% cross team collaboration

20% international collaboration

SSERVI RESEARCH CONTRIBUTES TO:

12 NASA MISSIONS

3 OTHER AGENCY MISSIONS

10 MISSION CONCEPTS

10 SPACEFLIGHT INSTRUMENTS

In addition, SSTP provides additional support for mission planning and proposals

45 VIRTUAL EVENTS | 810 VIRTUAL PRESENTATIONS

SUPPORTED FOR SSERVI AND COMMUNITY

Virtual Events		Virtual Presentations	
EC & Site Visit	11	NESF	88
NESF	1	LunGradCon	85
LunGradCon	1	Site Visits	65
Focus Groups	4	Focus Meetings	19
Workshops / Seminars	2	Workshops / Seminars	34
ELS	1	LSSW	184
LSSW	6	LEAG	80
LEAG	3	SBAG	126
SBAG	2	MEPAG	30
MEPAG	1	OTHER	99
OTHER	12		

WEBSITE ANALYTICS

320K Users on Main SSERVI Website

SOCIAL MEDIA ANALYTICS

117K Twitter Followers

MISSIONS

Part of SSERVI's mission is to provide scientific, technical, and mission-defining analyses for relevant NASA programs, planning, and space missions, as requested by NASA. Because SSERVI P.I.'s and team members are recognized globally as subject-matter experts and leaders in their fields, there is naturally a lot of overlapping Mission involvement within SSERVI teams.

SSERVI-funded research contributes to a number of NASA and International missions, instruments and programs. Below are just some highlights from 2020; additional details of team contributions to missions, instruments and programs are included in the individual team reports.

MISSIONS/INSTRUMENTS

Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx)—CLASS, RISE2

Development and Advancement of Lunar Instrumentation (DALI)
- *Lunar Environmental Monitoring Station (LEMS)*—**GEODES**
- *SUBsurface Lunar Investigation and Monitoring Experiment (SUBLIME)*—**GEODES**
- *Seismometer for a Lunar Network (SLN)*—**GEODES**
- *Electrostatic Lunar Dust Analyzer (ELDA)* instrument—**IMPACT**

JUpiter ICy moons Explorer (JUICE) Mission—REVEALS

Lucy—CLASS

New Horizons—IMPACT, CLASS

Europa Clipper
- *MISE instrument*—**REVEALS**
- *Plasma Instrument for Magnetic Sounding (PIMS)* instrument—**REVEALS**
- *Radar for Europa Assessment and Sounding: Ocean to Near-surface instrument*—**REVEALS**
- *Surface Dust Analyzer*—**IMPACT**

Hayabusa 2—RISE2

Lunar Trailblazer—VORTICES

Martian Moons eXploration (MMX)—CLASS
- Pneumatic Sampler—**CLASS**

ManitobaSat-1—ICE-FIVE-0

Interstellar Mapping and Acceleration Probe (IMAP)
- *Interstellar Dust Experiment (IDEX)*—**IMPACT**

Volatile & Mineralogy Mapping Orbiter Mission Cubesat *- ESA Funded*—ICE-FIVE-0

BORE-II and the Clockwork Starfish Demonstrators on Blue Origins New Shepard Rocket—ESPRESSO

Sun Radio Interferometer Experiment (SunRISE)—NESS

Farside Array for Radio Science Investigations of the Dark Ages and Exoplanets (FARSIDE)—NESS

Polar Resources Ice Mining Experiment-1 (PRIME1)—CLASS

CubeSat Particle Aggregation and Collision Experiment (Cu-PACE)—CLASS

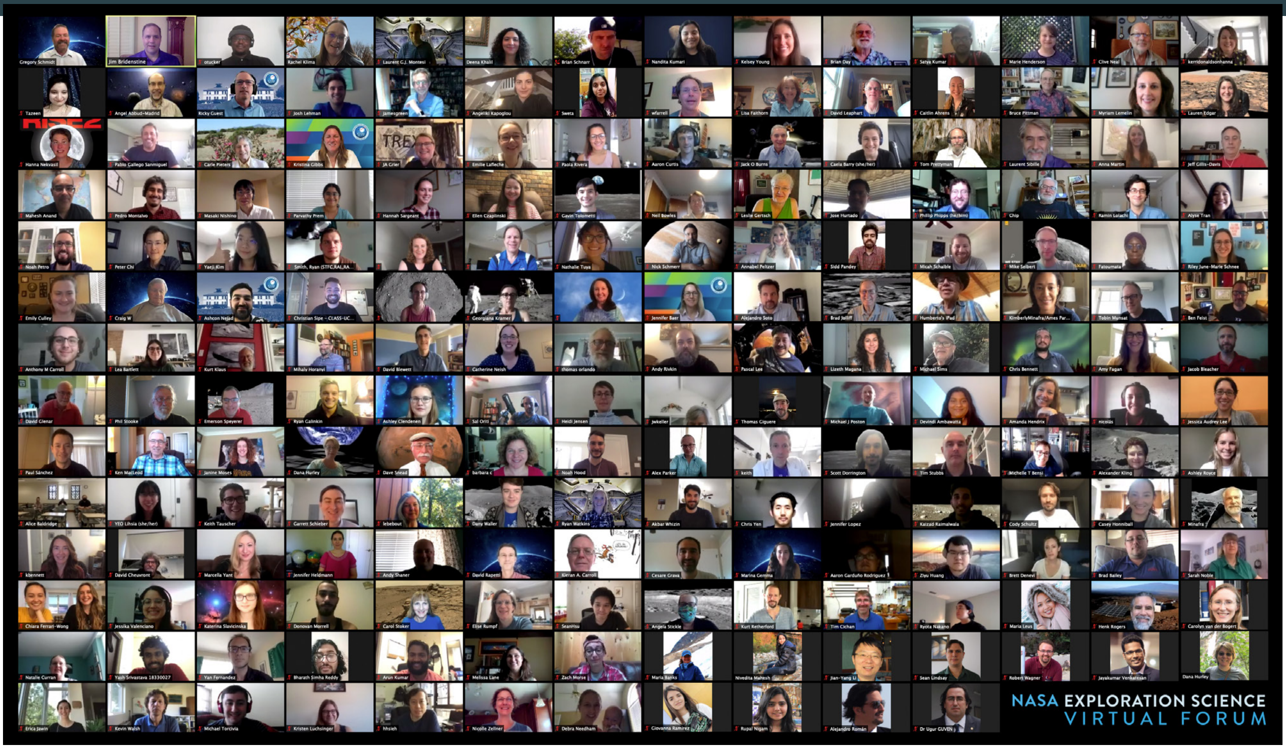
Lunar Compact Infrared Imaging System (L-CIRis)— CLASS

Janus—CLASS

PROGRAMS AND MISSION CONCEPTS

Artemis Sample Return
STMD Lunar Surface Technology Research (LUSTR) Proposal
Breakthrough Innovative and Game-changing (BIG) Idea Challenge
New Frontiers-5; Planetary Mission Concept Study
Payloads and Research Investigations on the Surface of the Moon (PRISM) Proposals
Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program
Dark Ages Polarimeter PathfindER (DAPPER) Mission Concept
PiPELiNE Mission Concept
Lunar Dust Mitigation SDT
Neutral Atom Spectrometer System instrument Concept
LunaR: A Versatile Raman Spectrometer for Lunar Exploration CSA Funded
Frozen Regolith Observation & Science Tools (FROST) CSA Funded
Solar System Workings Grant
Apollo Next Generation Sample Analysis Program (ANGSA)
Laboratory Analysis of Returned Samples (LARS)
Planetary Data Archiving and Tools (PDART) Program

NASA EXPLORATION SCIENCE FORUM 2020



SSERVI hosted the Virtual NASA Exploration Science Forum (NESF) July 8-10, 2020, which focused on sharing scientific discoveries, connecting researchers and promoting the Next Gen, and providing ways to interact personally. In addition to the oral scientific program, SSERVI secured support for presentations from the NASA Administrator as well as directors of SMD/PSD and HEOMD/AES and the NASA Chief Scientist. A key element was the inclusion of the Next Gen to the maximum extent possible, with Next Gen session Co-Chairs and a virtual student poster competition with associated required lightning talks. SSERVI also hosted three virtual focus group meetings in conjunction with the Forum, and provided virtual collaboration support for LunGradCon 2020. SSERVI hosted 100+ virtual posters in two poster sessions. Each poster had its own webpage including the poster, contact information, a comment section and a recorded presentation, and an active Zoom room during a poster session. The poster session is now being used as a model for efforts within and outside of NASA due to its success.

Virtual Forum Objectives:

The design of the poster sessions was one of the significant innovations in the 2020 Forum, as the SSERVI team sought to promote as much engagement between poster authors and visitors as possible. The goal was also to assure that all poster presenters, but especially student presenters, were guaranteed some exposure.

Another innovation was to have each oral session co-chaired by a senior and an early career scientist. This was proposed by the SSERVI team to the designated session chairs who readily agreed to work with co-facilitators. The intent was to provide opportunities for younger people to be seen and to contribute in a public and visible way.

The SSERVI team also recognized that the follow up discussions and impromptu conversations after the end of oral sessions that happen naturally in an in-person meeting would not be happening in the virtual space. To try and address this, the SSERVI team built into the Forum design and supported in real-time additional discussion periods that overlapped with breaks, after the formal sessions ended.

At the Forum's start, SSERVI leadership talked about the efforts to bring new elements into the three-day event, such as those described above and stressed the importance of community feedback through the post Forum survey.

EXPLORATION SCIENCE FORUM HIGHLIGHTS

FORUM HIGHLIGHTS

- 1 NASA Administrator Address
- 2 Panels
- 77 Presentations
- 103 Virtual Posters with Private Zoom rooms for discussion
- 12 Student / Early Career Session Co-Chairs
- 17 Student Lightning Talks
- 5 Professional Awards
- 3 Student Poster Awards
- 64.12% very satisfied, surprisingly no one was dissatisfied
- 95.31% gained new insights. Expanding perspective was highest
- 73.33% of poster authors received feedback on their posters

WEBSITE STATS

- NESF website viewed 25,000 times by 3,500 users
- Poster pages have been viewed 3,200 times
- Over 500 Twitter users clicked on NESF2020 links

ATTENDEE DATA

~ 2,200 attendees from the United States

~300 attendees from India

~100 attendees from the United Kingdom

~100 attendees from Canada

~70 attendees from Australia

~65 attendees from Colombia

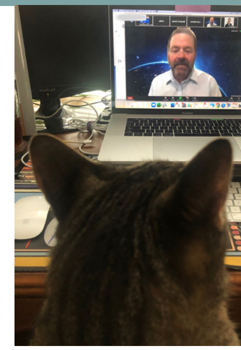
~50 attendees from China

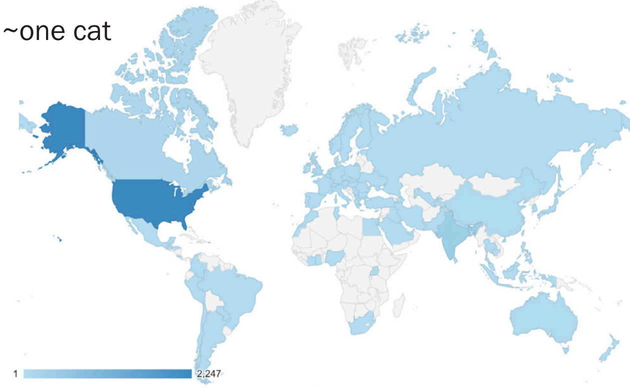
~40 attendees from France

~40 attendees from Japan

~35 attendees from Germany

~one cat

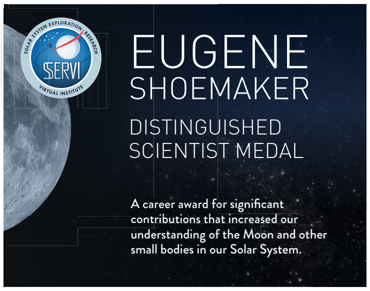


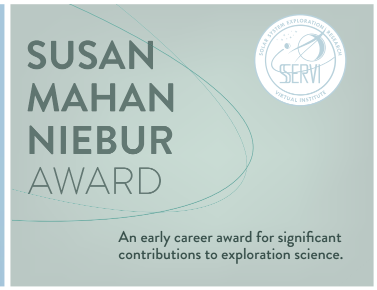


SSERVI Central Staff ran the all-virtual NESF during COVID shelter-in-place orders from their home offices.

NASA EXPLORATION SCIENCE FORUM AWARDS

At the NESF, SSERVI presents awards as a means of honoring key individuals in the community: the Eugene Shoemaker Medal for lifetime scientific achievement, the Michael J. Wargo Award for outstanding achievement in Exploration Science, the Susan Mahan Niebur Award for early career achievement, and the Angioletta Coradini Mid-Career Award.





AWARD NOMINATIONS

SSERVI awards are open to the entire research community; recipients need not reside in the U.S. nor be a U.S. citizen. Nominations are welcome at any time at: https://sservi.nasa.gov/awards/submit but must be submitted by March 31st for consideration in that calendar year. Winners are formally presented with the awards at the annual Exploration Science Forum each summer.

More information on these awards and recipients, along with past awardees, can be found at: https://sservi.nasa.gov/awards

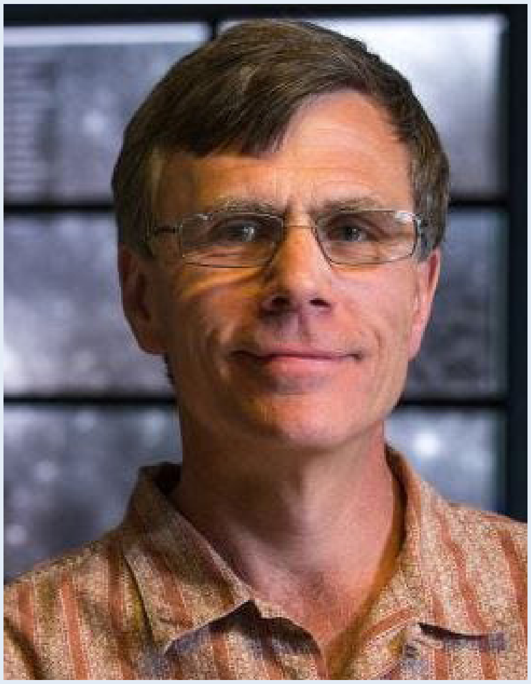
Eugene Shoemaker Distinguished Scientist Medal

The 2020 Eugene Shoemaker Distinguished Scientist Medal, named after American geologist and one of the founders of planetary science, Eugene Shoemaker (1928-1997), is awarded to Bradley L. Jolliff for his significant scientific contributions throughout the course of his career. The award includes a certificate and medal with the Shakespearian quote “And he will make the face of heaven so fine, that all the world will be in love with night.”

Dr. Bradley L. Jolliff is Professor of Earth and Planetary Sciences and Director of the McDonnell Center for Space Sciences at Washington University. He received his Ph.D. from South Dakota School of Mines and Technology, and his research is focused on the study of minerals and rocks of the Earth, Moon, Mars, and meteorites, and what they reveal about conditions of formation and planetary processes over the past 4.5 billion years. As a member of the Lunar Reconnaissance Orbiter Camera science team, he investigates the surface of the Moon, relating what can be seen from orbit to what is known about the Moon through the study of lunar meteorites and Apollo samples. He has made significant scientific contributions in sample analysis, surface science, and remote sensing, as well as laboratory studies. Professor Jolliff also leads the Washington University team that is part of NASA’s Apollo Next Generation Sample Analysis (ANGSA) program. SSERVI is very pleased to present Professor Jolliff with the 2020 Eugene Shoemaker Distinguished Scientist Medal.

Michael J. Wargo Exploration Science Award

The Michael J. Wargo Exploration Science Award is an annual award given to a scientist or engineer who has significantly contributed to the integration of exploration and planetary science throughout their career. Dr. Michael Wargo (1951-2013) was Chief Exploration Scientist for NASA's Human Exploration and Operations Mission Directorate and was a strong advocate for the integration of science, engineering and technology. The 2020 Michael J. Wargo Exploration Science Award is given to Mark Robinson.



Mark Robinson. Photo credit: Charlie Leight/ASU

Dr. Robinson is a Professor of Geological Sciences in ASU's School of Earth and Space Exploration, a member of the NASA Advisory Council, and serves as the Principal Investigator for the imaging system on NASA's Lunar Reconnaissance Orbiter (LRO). LRO has collected a treasure trove of data, making an invaluable contribution to our knowledge about the Moon, and Dr. Robinson's stewardship has enabled numerous groundbreaking discoveries that have created a new picture of the Moon as a dynamic and complex body.

Throughout his career, Dr. Robinson's investigations have used a variety of remote sensing techniques and datasets from a dozen NASA missions. He worked on the Clementine mission–the first U.S. spacecraft launched to the Moon in over 20 years– which provided our first complete look at the lunar surface, including the poles, and found evidence of ice in the bottom of a permanently shadowed crater at the Moon's south pole. His collaborative research on old data resurrected from the Mariner 10 mission to Mercury (1973-1975) extracted compositional information about the surface rocks that had lain hidden in the old data for roughly 20 years.

Much of his current research efforts focus on expanding on our knowledge of the lunar surface, paving the way for future human and robotic exploration of the Moon. His discoveries and research developments have set up a scientific framework through which to challenge and improve our understanding of processes throughout the solar system. SSERVI is pleased to present Mark Robinson with the 2020 Michael J. Wargo Exploration Science Award.

"Each of these extremely dedicated individuals has helped advance our scientific understanding of the Moon and other target bodies," said Greg Schmidt, Director of SSERVI. "Their outstanding research efforts are vital to the ambitious activities we hope to achieve in exploring the Solar System with robots and humans."

Angioletta Coradini Mid-Career Award

The SSERVI Angioletta Coradini Mid-Career Award is given annually to a mid-career scientist for broad, lasting accomplishments related to SSERVI fields of interest. Angioletta Coradini (1946-2011) was an Italian planetary scientist who has inspired astronomers around the world. The 2019 Angioletta Coradini Mid-Career Award is given to Dr. Harald Hiesinger, Professor of geological planetology at the university of Münster in Germany.

Professor Hiesinger is a member of both the American and European Geophysical Unions, and the Geologic Society of America. He has been recognized with multiple Achievement Awards from the European Space Agency, and has received NASA Group Achievement Awards as part of the Dawn Mission Science Team and the Lunar Reconnaissance Orbiter (LRO) Team. In 2014 the International Astronomical Union named asteroid 26811 Hiesinger after him.

Prof. Hiesinger has been a strong collaborator with SSERVI and its research teams; his research into planetary processes and the geologic evolution of terrestrial planets and moons has advanced our understanding of the lunar chronology and helped constrain the age of the South Pole-Aitken basin and other potential lunar landing sites. He recently detailed Mission preparations for Commercial In-Situ Resource Utilization Demonstration and is engaged in wide array of other projects. In addition to being widely published and credited with numerous journal articles, his many contributions and achievements make him a highly worthy recipient of the 2020 Angioletta Coradini Mid-Career Award.

Susan Mahan Niebur Early Career Award

The 2019 Susan Mahan Niebur Early Career Award is an annual award given to an early career scientist who has made significant contributions to the science or exploration communities. Recipients of the Susan M. Niebur Early Career Award are researchers who are no more than ten years from receiving their Ph.D., who have shown excellence in their field and demonstrated meaningful contributions to the science and/or exploration communities. Susan Mahan Niebur (1978-2012) was a former Discovery Program Scientist at NASA who initiated the first-ever Early Career Fellowship and the annual Early Career Workshop to help new planetary scientists break into the field. This year the prize is presented to Dr. Ryan Watkins, a Research Scientist with the Planetary Science Institute (PSI), and Prof. Amy Fagan, a former Postdoctoral Fellow at the Lunar and Planetary Institute now at Western Carolina University.

Dr. Watkins' research focuses on integrating remote sensing data sets to characterize the physical and compositional properties of airless bodies, with particular emphasis on the lunar surface. She specializes in using photometry to understand physical and compositional properties of the lunar surface, and in integrating planetary data sets to assess landing site safety hazards for future missions. Dr. Watkins obtained dual B.S. degrees in Physics and Space Science from the Florida Institute of Technology in 2010, and her Ph.D. in Earth and Planetary Science from Washington University in St. Louis in 2015. Before joining PSI as a Research Scientist, she served as a Postdoctoral Research Associate at Washington University in St. Louis with Dr. Bradley Jolliff.

Dr. Watkins is actively engaged in service and leadership within the planetary science community. She serves on the Organizing Committee for the Next Generation Lunar Scientists and Engineers (NextGen) group, on the Executive Committee for the Lunar Exploration Analysis Group (LEAG), on the Steering Committee for the Equity, Diversity, and Inclusion (EDI) Working Group, and on Blue Origin's Science Advisory Board for their Blue Moon lander project. In addition to research and planetary community service, Dr. Watkins regularly participates in Education and Public Outreach in her local community, and with the Solar System Exploration Virtual Institute (SSERVI) Toolbox for Research and Exploration (TREX) team. SSERVI is very pleased to co-present the Susan Niebur award to Dr. Ryan Watkins.

Professor Amy Fagan received her B.S. in Geology with Honors from Washington and Lee University in 2006, and her Ph.D. in Lunar Petrology from University of Notre Dame in 2013. Prof. Fagan's doctoral research under the guidance of Dr. Clive Neal focused on volcanic and impact processes on Mars and the Moon. Using Mars Orbiter Laser Altimeter (MOLA) data, she examined the morphology of impact craters and subglacial volcanoes on Mars' surface, while the bulk of her research examined the chemical composition of Apollo basalts and impact melt products.

In 2009, she was a Lunar Exploration Student Intern Supervised by Dr. David Kring, as part of SSERVI's Center for Lunar Science and Exploration (CLSE) Team, quickly rising to the level of graduate student researcher, and then postdoctoral fellow. In 2012 she received the Lunar and Planetary Institute Career Development Award.

Her service to the professional activities of this community has been exemplary: She has served on several NASA Science Mission Directorate Review Panels; as a NASA Lunar Exploration Analysis Group (LEAG) member and Operations Chair; a COSPAR Rapid Response Specific Action Team Member; a LPSC Session Co-Chair; a NESF Co-Organizer, Session Co-Chair, and Panel Member; was a Co-Organizer of the first annual Lunar graduate student conference (LunGradCon) at NASA Ames in 2010, and Co-organizer of the annual Next Generation of Lunar Scientists and Engineers (NGLSE) workshop. Dr. Fagan is now Associate Professor in the Geosciences and Natural Resources Department at Western Carolina University, and is currently a NASA Apollo Sample Principal Investigator. SSERVI is honored to co-present the Susan Niebur award to Professor Amy Fagan.

Congratulations to Drs. Jolliff, Robinson, Hiesinger, Watkins and Fagan for their achievements and contributions!

2020

NASA Exploration Science Forum Student Poster Competition winners*:*

First place was awarded to **Ryota Nakano** for the poster *"Mass Shedding Activities of Asteroid (3200) Phaethon Enhanced by its Rotation."*

Second place was awarded to **Marina Gemma** for the poster *"Multi-Dimensional Characterization of Mineral Abundance in Ordinary Chondrite Meteorites."*

Third place was awarded to **Kristen Luchsinger** for the poster *"Pushing the Boundaries of Lunar Ice: Vertical Volatile Transport in Seasonally Shadowed Regions."*

NASA Exploration Science Forum 2020 Student Winners

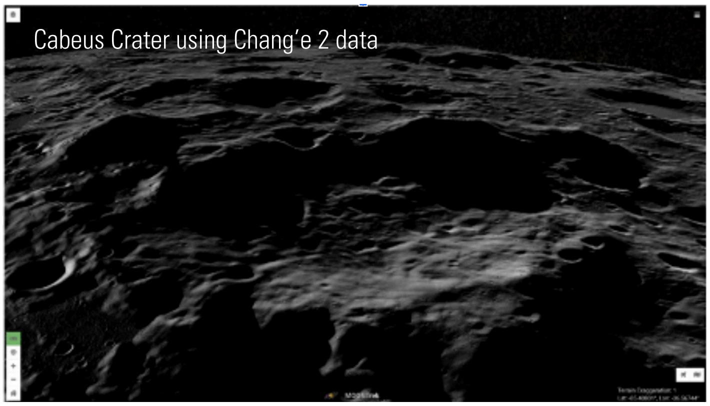
The annual Student Poster Competition held each year at the NASA Exploration Science Forum provides motivation, encouragement, and most of all recognition to the most promising scientists of the future. The contest is always very competitive with high-quality submissions. Selection criteria include the originality of the research and its impact to science and exploration, the merit of the experiment design and rigor of results, the visual quality and clarity of the poster layout—including accessibility to the non-expert, and effectiveness in communicating the topic during the lightning talk. 1st, 2nd and 3rd place winners received a $1000 travel grant. Selections were made by votes of a committee of scientists and SSERVI management.

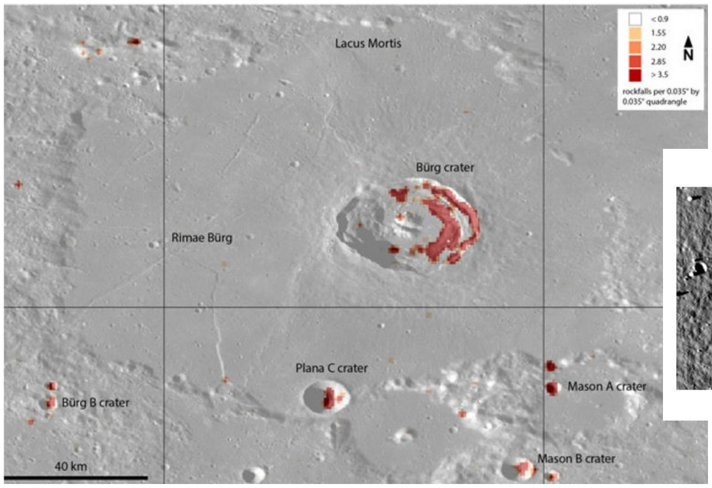
SOLAR SYSTEM TREKS PROJECT

The role of Solar System Treks Project (SSTP) as an online tool for remote planning was more prominent than ever in 2020 given the COVID-19 pandemic and telework mandates. In spite of these challenges, SSTP has collaborated with various groups within NASA and its commercial partners in preparation for imminent new missions to the Moon. These activities include generation of new high-resolution mosaics and Digital Elevation Maps (DEMs), introduction of new analytic tools, significant enhancements to portal interface and search capabilities, and the continuing integration of new data products. Throughout the year SSTP continued to advance the science and exploration goals of NASA. Just as the Agency has focused much of its attention on the Moon, SSTP has devoted significant efforts this year to updating Moon Trek and its application to lunar science and exploration. SSTP is also engaging with NASA's commercial partners through the Commercial Lunar Payload Services (CLPS) program. It has been tasked with providing detailed visualization and analysis capabilities for proposed future human and robotic landing sites on the Moon, and is an integral participant in NASA's Mars Human Landing Site Selection process.

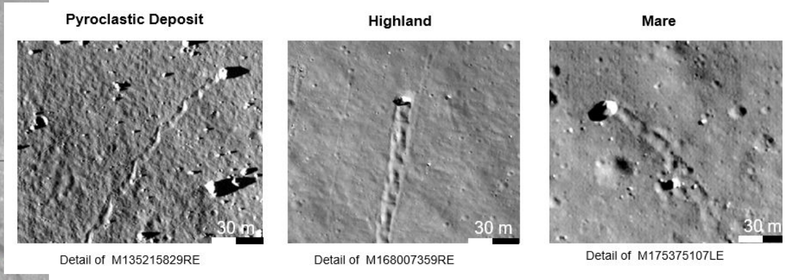
SSTP is actively working to integrate advanced machine learning-based rockfall detection methodologies into Moon Trek as a new analytic tool. This has great potential to characterize geotechnical properties of regolith in diverse lunar environments including Permanently Shadowed Regions (PSRs). The integration of our rockfall and boulder detection capabilities and probabilistic lunar seismic hazard analyses will benefit exploration planning and extend our understanding of lunar geophysics.

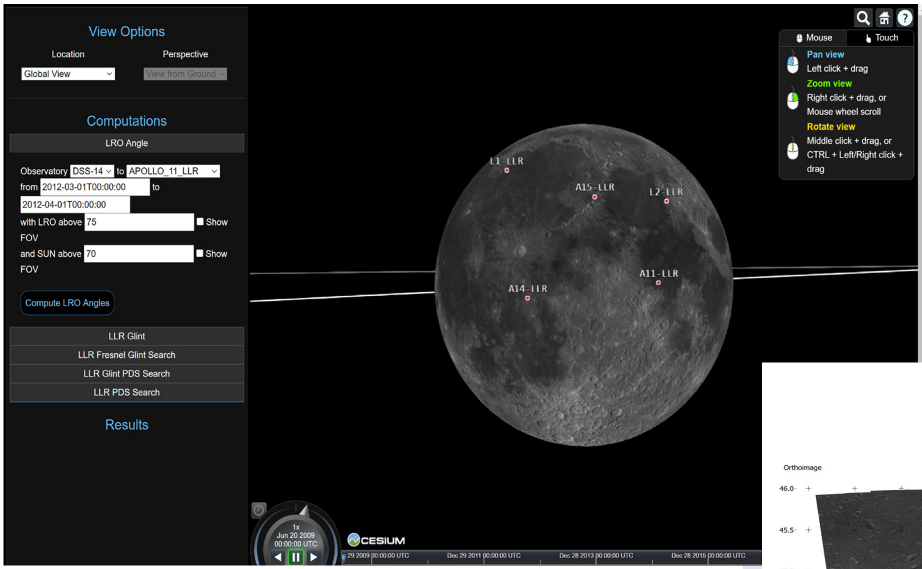
Work this year in developing an automated data pipeline has been a critical key in advancing our high-priority goals of enhancing the distribution and usage of Planetary Data System (PDS) data, and supporting SMD and HEOMD planning for upcoming lunar missions. Researchers are now able to more quickly assemble high resolution data products including orthomosaics and DEMs that are in high demand from various PDS users.





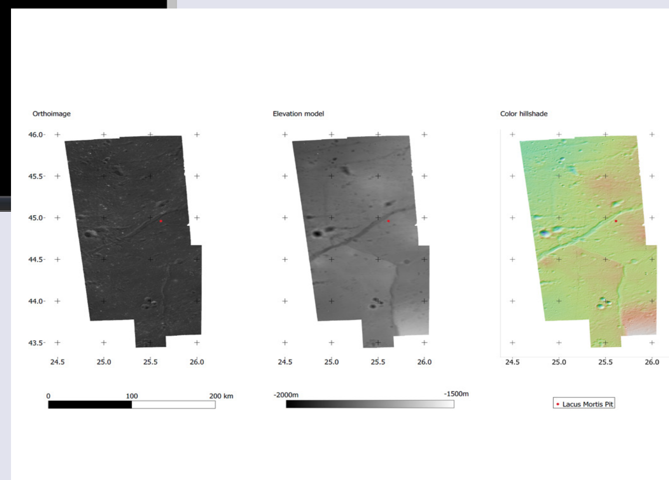
Rockfall Detection: Rockfall paths serve as geotechnical probes. Tool returns heat map and text file with details. Credit V.Bickel.





◀ LLR Geometry tool.

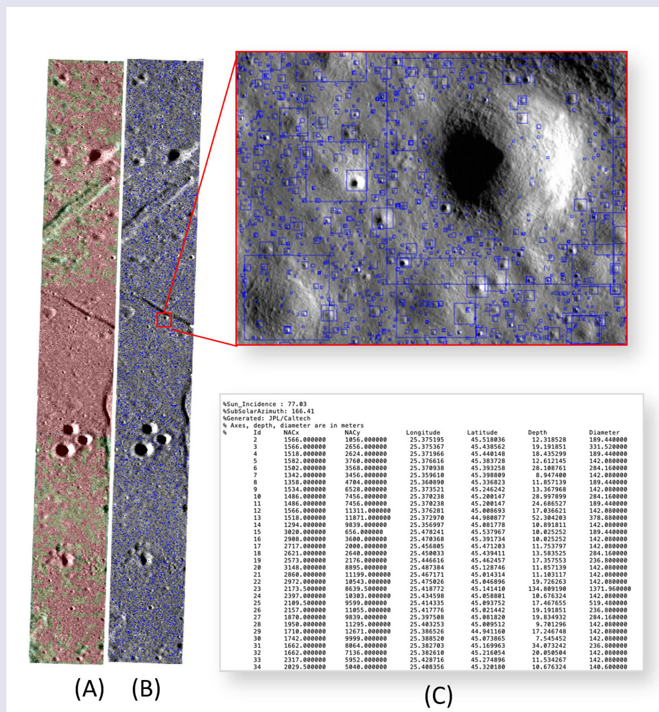
▼ Examples of types of data generated by the automated pipeline.



The integration and release of the Lunar Laser Reflector (LLR) geometry tool in Moon Trek in partnership with the Italian Institute of Nuclear Physics (INFN) will facilitate planning of Lunar Laser Ranging studies. These studies will refine our understanding of the Moon's orbit as well as lunar surface geodesy, lunar geophysics, and a range of fundamental physics topics including tests of general relativity and new gravitational physics.

During the past year, the project enhanced the technologies used in SSTP's existing portals, extended these technologies to additional planetary bodies, partnered with existing and future missions in mission planning, data visualization, and analytics, and played key roles in NASA's efforts in STEM engagement to learners of all ages. The project is supporting NASA's collaboration with its international space agency partners including JAXA (Japan), ESA (Europe), KARI (S. Korea), ASI and INFN (Italy), and AEM (Mexico).

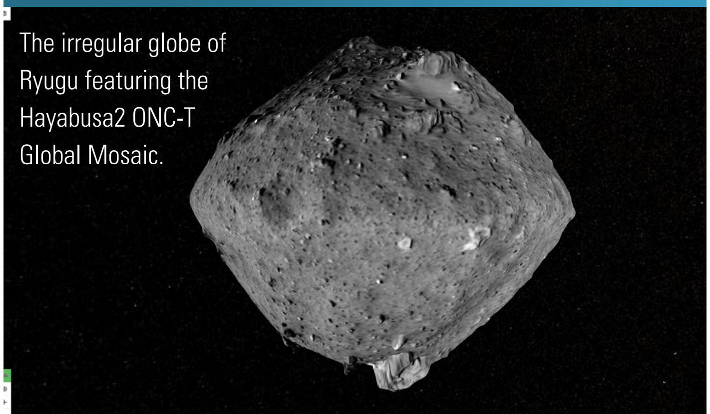
In addition to the Solar System Treks home website (https://trek.nasa.gov) that provides unified, easy access to all of the portals, SSTP offers seven online portals: Moon Trek, Mars Trek, Ceres and Vesta Trek, Titan Trek and Icy Moon Trek, Mercury Trek and, during the course of FY20, SSTP released two new portals for the near-Earth asteroids Bennu and Ryugu.



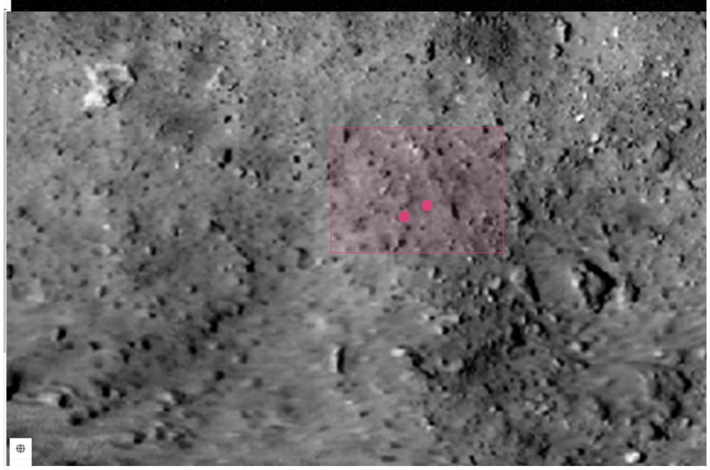
Crater Detection: (A) Hazard heat map (B) Craters labeled with bounding boxes (C) Text file lists coordinates, depths, diameters, and confidence value.

The new portal for the near-Earth asteroid Bennu was released in collaboration with the OSIRIS-REx mission. Our continuing partnership with JAXA resulted in the release of a new portal for the asteroid Ryugu featuring data from the Hayabusa2 mission, as well as the release of an updated version of the Mercury Trek Portal.

RYUGU TREK

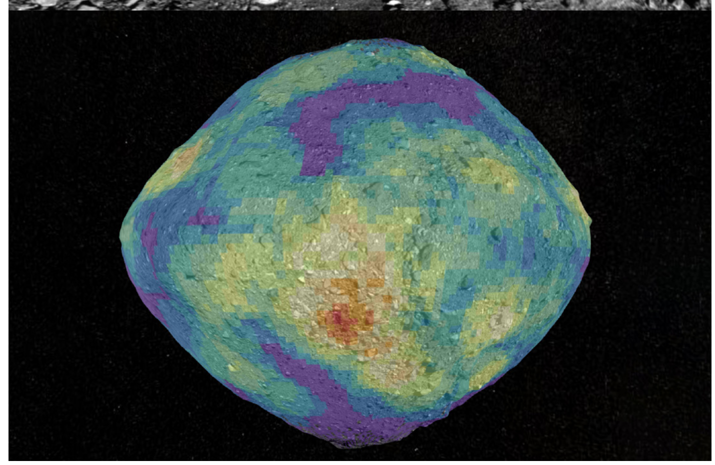


The irregular globe of Ryugu featuring the Hayabusa2 ONC-T Global Mosaic.



View from Hayabusa2 tour in Ryugu Trek.

BENNU TREK



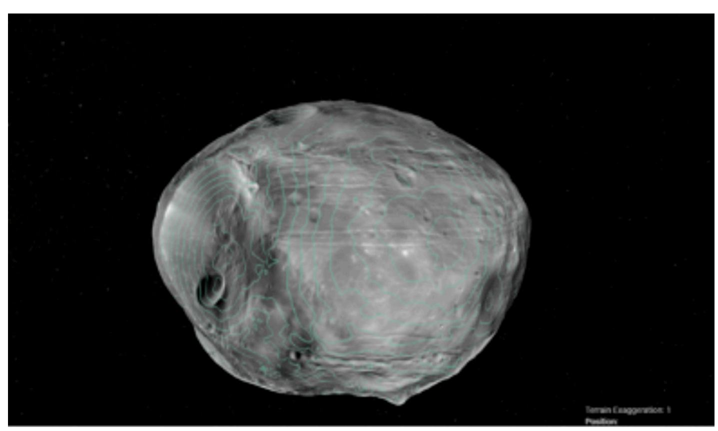
Nightingale site visualization and global PolyCam view blended with rock abundance data in Bennu Trek.

New Portals Under Construction

SSTP continues to collaborate with the Japanese Space Agency in support of the upcoming Martian Moon eXploration (MMX) mission on a prototype portal for Mars' moon Phobos. This effort requires collaborating with a number of international partners including the ESA's Mars Express Mission. This year the new Phobos Trek prototype was featured in numerous presentations and conferences.

A new Earth Trek portal will be differentiated from other tools such as Google Earth and NASA WorldWind by specializing in topics of particular relevance to NASA SMD and HEOMD. A key area of focus will be facilitating visualization, analysis, comparison, and visualization of data for key terrestrial analog sites.

These are just a few examples of how SSTP and its partnerships are being used to advance science and exploration. Additional examples and details can be found in the full SSTP Annual report found at sservi.nasa.gov/library/SSTP2020 or by visiting trek.nasa.gov.



Phobos with gravity contours in Phobos Trek prototype.

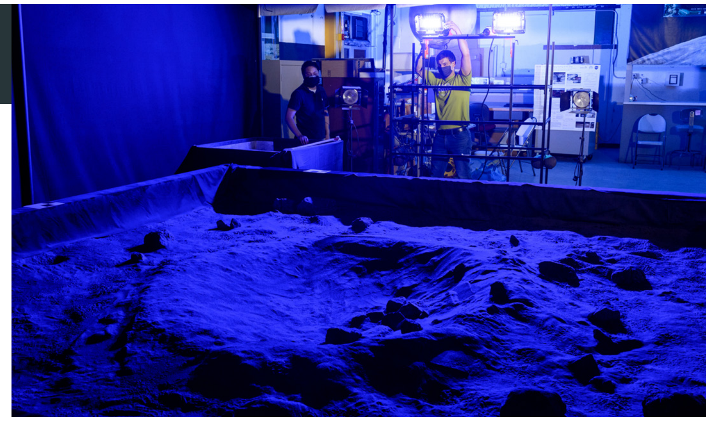
FACILITIES-REGOLITH TESTBED

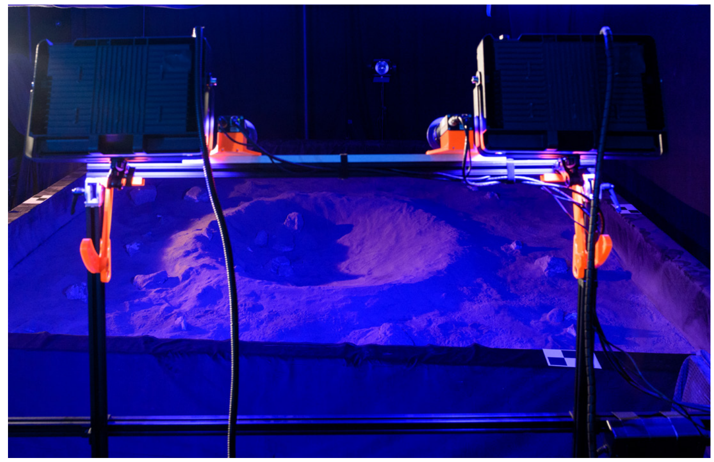
SSERVI manages the Regolith Testbed/Lunar Lab at NASA Ames, which contains an assortment of planetary simulants including eight tons of JSC-1A lunar lowlands regolith simulant. The facility is available to SSERVI teams as well as other NASA researchers and partners.

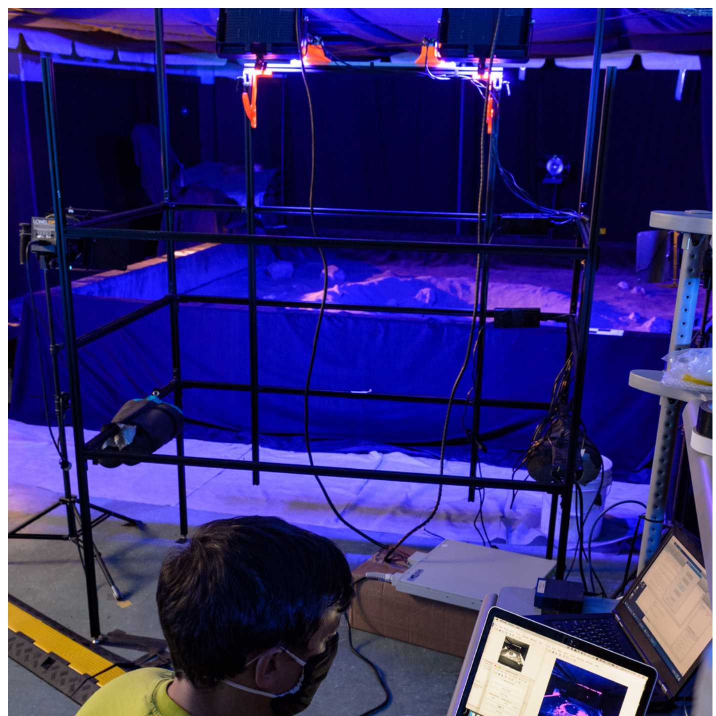
The regolith testbed was upgraded in 2020 with a new ventilation system, along with all safety requirements for COVID, and passed inspection for return to work. The facility is fully operational and has been supporting the NASA VIPER mission in testing Long Range Terrain Characterization for Productive Regolith Excavation, hazard avoidance, and resource identification and extraction techniques.

SSERVI also provided cost estimates for Human Landing System (HLS) Phase A work in preparation for precision navigation and guidance system tests. Key contributors to NASA's SLS are planning to use the testbed to apply novel approaches to analyze and optimize the performance of fault-tolerant flight computing and human-rated flight software. SSERVI, in collaboration with the CLASS team's Exolith lab, also supplied simulants to NASA's Development and Advancement of Lunar Instrumentation (DALI) program. The testbed is fast becoming a key lunar research lab and continues to serve as a potential feeding ground for commercial collaborations.

SSERVI has provided the Regolith Testbed and an assorted collection of lunar, asteroidal, and planetary soil simulants to researchers and private companies in support of NASA missions; specifically our support has helped companies like Made in Space, who will be 3D printing on the ISS with our JSC-1A Regolith Simulant. The facility has also been highlighted by Ames Research center as an unique lunar research capability for other potential private industry partners looking to support NASA's missions to the Moon. Expanding the testbed into a larger Planetary Soils Lab and Mechanics facility with additional test beds, including an anorthosite-specific test bed, will further enhance capabilities for future research and development.







SSERVI Regolith Testbed At NASA's Ames Research Center, the VIPER team tests out several robust LED lighting systems – including blue lights and other wavelengths – to see which would offer the best optical performance for the rover on the Moon. The Ames-based team will pass their findings on to VIPER teammates at NASA's Johnson Space Center in Houston where the lights will eventually be built.

FACILITIES OPEN TO THE COMMUNITY

The following SSERVI-sponsored facilities can be made available to the broader scientific community. Interested parties should engage the facility POC to discuss scheduling time at the facility, along with any potential associated costs. Research activities that took place using team-supported facilities can be found in the individual team reports.

Dust Accelerator Laboratory (DAL) (U. of Colorado)

A 3 MV linear electrostatic dust accelerator which is used for a variety of impact research activities as well as calibrating dust instruments for space application.The 3 MV Pelletron generator is capable of accelerating micron and submicron particles of various materials to velocities approaching 100 km/s.
Contact: http://impact.colorado.edu/facilities.html

Ultra High Vacuum (UHV) & Ice and Gas Target Chambers (U. of Colorado)

Dedicated chambers that can be directly connected to the Dust Accelerator Laboratory for impact experiments requiring very clean conditions with exceptionally low background gas pressure, extreme cold temps, or various atmospheric gas pressures.
Contact: http://impact.colorado.edu/facilities.html

Reflectance Experiment Lab (RELAB) (Brown University)

Spectroscopic data can be obtained for compositional information relevant to planetary surfaces. High precision, high spectral resolution, bidirectional reflectance spectra of Earth and planetary materials can be obtained using RELAB.
Contact: http://www.planetary.brown.edu/relab/

Vibrational Spectroscopy Lab (Stony Brook University)

Spectroscopic tools allow examination of geologic materials similar to those that are present on Mars, the Moon, or other solar system bodies for better interpretations of remote sensing data.
Contact: http://aram.ess.sunysb.edu/tglotch/

Physical Properties Lab (U. Central Florida)

The density lab includes: (1) A Quantachrome Ultrapycnometer 1200. (2) A new custom-built pycnometer for larger samples. A special insert for thin slabs (up to ¼ in.). Both pycnometers have uncertainties of better than 0.5%. (3) ZH Instruments SM-30 magnetic susceptibility meter. (4) A fieldspec reflectance spectrometer with a wavelength range of 0.4-2.5 microns.
Contact: britt@physics.ucf.edu

GSFC Radiation Facility (NASA GSFC)

A dedicated 1 MeV proton beam line used to create radiation-stimulated defects in materials to help determine low energy H retention effects.
Contact: william.m.farrell@nasa.gov

Microgravity Drop Tower (U. Central Florida)

The drop tower provides a zero-G experience (0.7sec of freefall). An LED backlight helps track individual ejecta particles. Images are recorded with a high-resolution camera at 500 frames/second, which allows tracking of individual particles.
Contact: josh@ucf.edu

Regolith Testbeds (NASA's Ames and Kennedy Space Centers)

The 4m x 4m x 0.5m testbed at NASA Ames is filled with 8 tons of JSC-1A regolith simulant. Excellent for investigations in resource prospecting and regolith.
Contact: joseph.minafra@nasa.gov

FOCUS GROUPS

SSERVI focus groups are community-organized and address a wide variety of current scientific, technical and programmatic topics. They are deliberately organized topically to allow participants to delve deeply into specific research areas, and have broad membership from the community, both inside and outside of SSERVI. Participants interact online or in-person and give actionable insights from their knowledge of planetary science, human exploration, space systems and technology, and missions.

SSERVI focus groups support the community in communicating and coordinating their research across disciplinary, organizational, divisional, and geographic boundaries. Focus groups seek to advance exploration science in different areas by leveraging the power of a collaborative community-wide network. SSERVI Central provides the infrastructure and hosts these meetings as requested. It also provides opportunities to foster new focus groups to address interdisciplinary topics, to explore collaborative technologies and innovative ideas for implementing novel networking strategies, and to develop community standards.

In 2020, SSERVI sponsored eight focus groups and retired one topic, the Apollo Lunar Surface Experiments Packages (ALSEPs) Data Recovery. The focus group topics are 1) Bombardment History of the Solar System, 2) Dust, Atmosphere, and Plasma (DAP), 3) Equity, Diversity, and Inclusion (EDI), 4) Field Analogs, 5) Payloads and Instrumentation, 6) South Pole Aitken Basin, 7) Space Commerce, and 8) Volatiles. Typically the focus groups gather during the NASA Exploration Science Forum, but this year, that element was cancelled as the meeting was made all virtual. Four of the focus groups were active with virtual meetings and have provided summaries of their activities here. For more information and contact information for focus group leads visit https://sservi.nasa.gov/focus-groups/

Equity, Diversity, and Inclusion (EDI) Focus Group-NEW

Since its inception in mid-2020, the SSERVI EDI Focus Group has made significant progress in developing our capacity to address the concerns presented by Director Gregory Schmidt in his public statement of June 10, 2020. (View Schmidt's statement at https://sservi.nasa.gov/articles/15083/) Dr. JA Grier (PSI) of the SSERVI TREX Node has stepped forward as Focus Group Lead. We have created the EDI-Focus members list, inviting interested stakeholders from science, education, EDI, industry, sci-comm, and engineering with broad interests in the Moon, asteroids, and human exploration of space. The group now exceeds 70 members; to request to be added visit https://groups.google.com/u/0/a/psi.edu/g/edi-focus?pli=1. Zoom meetings are scheduled every other week for face-to-face interactions, with additional business conducted asynchronously via email. Creating and administering an internal information survey has identified group needs, resources, and desired goals.

In addition to the creation and kick-off of the Focus group, activities have included: supporting members individual local EDI efforts, developing the group's capacity to conduct EDI work, partnering with others in the EDI community, and progressing on initiatives for positive change. During meetings, group members report on their local/national projects and concerns, and get input/feedback from the rest of the group. Most of the meetings include a speaker who presents on some aspect of EDI programs or on important background/professional development. We have created a resource list with links, articles, books, projects, and more that members can edit and reference for personal learning. A resource list was created with links, articles, books, projects, and more that members can edit and reference for personal learning. Communication was established with other bodies conducting EDI work such as LEAG, the NASA EDI

Equity, Diversity, and Inclusion Focus Group Artwork.

Working Group, LSIC, and representatives of the AAS DPS, AGU, and LPSC. Members have attended many additional conferences and have brought that information back to the Focus Group, including SACNAS, Space Science in Context, and the Society for Black Physicists. An EDI Best Practices document was initiated for use by members and SSERVI-associated personnel. The group has supported SSERVI in addressing EDI within the mentorship program, and will offer input into revising the requirements and selection of SSERVI prize winners. The group moves forward to position SSERVI as a leader in space science EDI. Visit the EDI Focus Group page (https://sservi.nasa.gov/focus-groups/) for more information.

Dust, Atmosphere, and Plasma (DAP) Focus Group

The SSERVI Dust and Plasma Focus Group was created under the NASA Lunar Science Institute and has convened each year at the Exploration Science Forum since its inception. Members have also attended and presented at several Dust-focused workshops that have been sponsored through the NASA Lunar Surface Science Workshops, and the Lunar Science Innovation Consortium. Membership is open to anyone with an interest in dust and plasma processes and interactions with planetary surfaces, and participation is entirely voluntary. Typically, ~25 members attend meetings; the group composition is primarily academics, but also includes government (primarily NASA centers), industry, and technical representatives. Recent group meetings have focused on the interest of those outside of the typical dust and plasma community, such as engineers, instrument providers, and flight/lander providers, and how best to communicate issues across the science and engineering spectrum. A listserv and communication forum serve to connect members, both to advertise upcoming relevant events or to highlight new science. Previous meetings recordings are available at https://sservi.nasa.gov/DAP-focus-group.

Analogs Focus Group

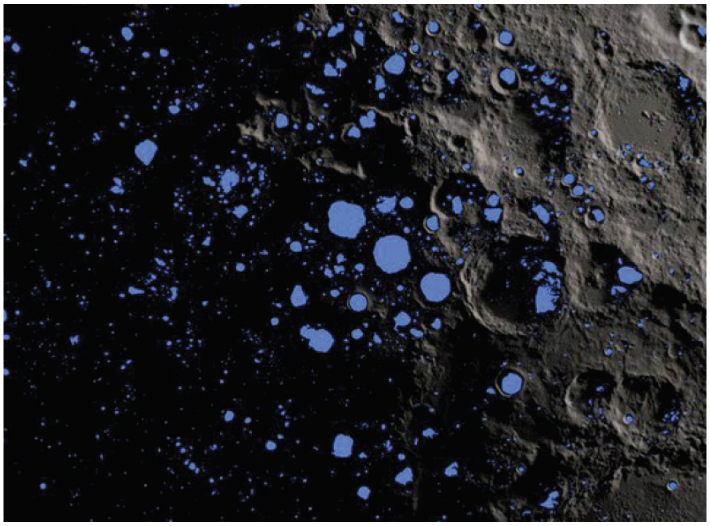
The SSERVI Analogs Focus Group was established by RESOURCE P.I. Heldmann, RESOURCE Co-I Lim, and RISE2 P.I. Glotch. Terrestrial analog field studies offer the unique opportunity to prepare for both robotic and human planetary surface missions. Analogs provide the opportunity to conduct studies and tests related to science, mission operations, and technology in a relevant environment at relatively low cost and risk. The SSERVI Analogs Focus Group aims to bring together over 200 members of the community to discuss and review various aspects of fieldwork including, but not limited to, field sites, deployment logistics, field instrumentation, concepts of operations, software and hardware testing, etc. This Group currently hosts quarterly virtual seminars that are recorded and posted on the SSERVI website for later viewing.

The table below presents a list of Analogs Focus Group presentations that are available online for viewing at https://sservi.nasa.gov/analogs-focus-group/.

Seminar Title	Speaker
Analog Field Campaign Management and Logistics	Darlene Lim (NASA Ames Research Center)
Terrestrial Analog Fieldwork: Overview of Science and Exploration Research to Enable Lunar and Planetary Exploration	Jennifer Heldmann (NASA Ames Research Center)
Field and Sample Analogs in Preparation for Future Human Exploration of the Solar System	Timothy Glotch (Stony Brook University)
Martian Hydrothermal Analogs in Iceland	J.R. Skok (SETI Institute)
Geophysical Exploration at Planetary Analog Field Sites	Nicholas Schmerr (University of Maryland, College Park)
The Medicine is Real, the Space is Not: Lessons in Analog Medical Care from Four Extreme Environment Simulations	Sheyna Gifford (Rehabilitation Medicine, Washington University St. Louis, Health & Safety Officer for HI-SEAS IV) and Bonnie Posselt (Royal Air Force - Resident in Aviation and Space Medicine; AFRL, Wright-Patterson Air Force Base - Exchange Officer and PhD Candidate; Austrian Space Forum - Medical Officer)

Volatiles Focus Group

The SSERVI Volatiles Focus Group (Friends of Lunar Volatiles - FoLV), met 11 times in 2020. The FoLV listserv currently has 242 subscribers and the group meets monthly to discuss recent research results and other issues of interest to the community. Membership is open to anyone with an interest in solar system volatiles, and participation is entirely voluntary. Typically, 20-30 members dial in to monthly meetings. This year, research presentations were given by Jacob Kloos (York University), Ian Garrick-Bethell (UCSC) and Andrew Poppe (SSL/UC Berkeley), Rosemary Killen (NASA GSFC), Colin Hamill (APL), Lauren McGraw (NAU), Daniella Scalice (NASA Astrobiology), Jim Head (Brown University) and Shuai Li (UH Manoa), spanning a range of topics - from the seasonal migration of lunar volatiles (Kloos) to hydration on asteroids (McGraw) to the partnership between NASA and the Navajo Nation (Scalice). Beginning this year, recordings of most previous meetings will be available at https://sservi.nasa.gov/volatiles-focus-group. During a 'special edition' FoLV meeting in May, Julie Mitchell, in her capacity as Astromaterials Curator of Ices and Organics and Artemis Curation Lead at NASA JSC, led a discussion on how volatiles science could be advanced by lunar polar sample return. Meetings in January and June focused on discussions of white papers for the Planetary Science and Astrobiology Decadal Survey. FoLV members contributed to many white papers, including an overview of 'Lunar Volatiles and Solar System Science' submitted by FoLV lead Parvathy Prem together with 40 co-authors including many FoLV members.



ALSEP Data Recovery

The ALSEP Data Recovery Focus Group, originally established under NASA's then Lunar Science Institute, was retired in 2020 after the recovered ALSEP data was permanently archived in the Planetary Data System (PDS). The Apollo Lunar Surface Experiments Packages (ALSEPs) transmitted data to the Earth until September 1977, but when the observation program ended a large portion of these data went missing. The ALSEP Data Recovery Focus Group formed in 2010 for the purpose of searching, recovering, preserving, and analyzing the data that were not previously archived. One of the major achievements of the group was finding and extracting data from 450 historic ARCSAV tapes. The group also retrieved notes and reports left behind by the now deceased/retired ALSEP investigators at their home institutions, and re-analyzed the ALSEP data using the information from the recently recovered metadata (instrument calibration data, operation logs, etc.). The ALSEP Focus Group established a web portal at the Lunar and Planetary Institute, where ~700 ALSEP-related documents, totaling ~40,000 pages, have been digitally scanned and cataloged. Researchers can search and download these documents at www.lpi.usra.edu/ lunar/ALSEP/.

SSERVI Hosted Session at AGU

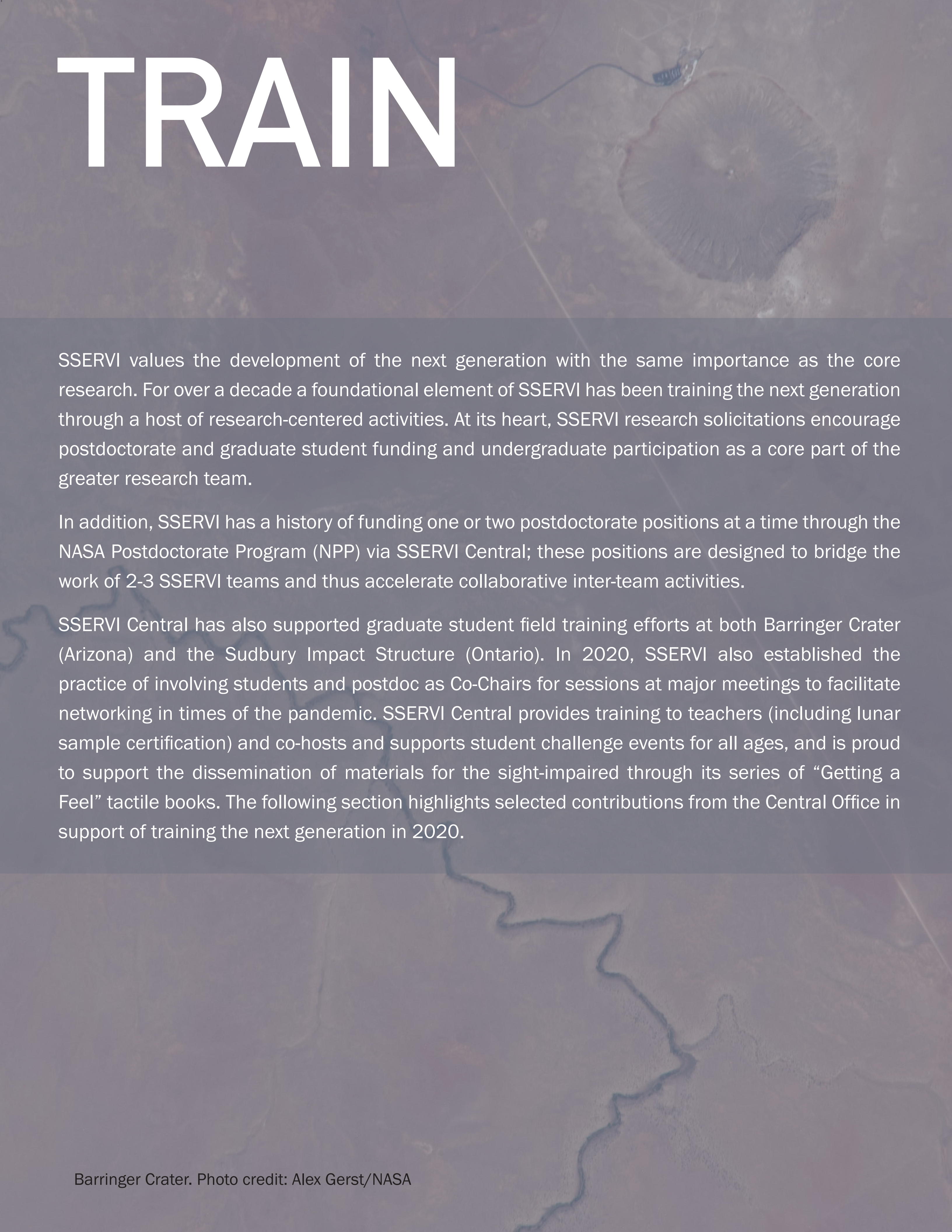
SSERVI hosted a three part oral session at the 2020 American Geophysical Union (AGU) virtual meeting this year on December 14th. The session was titled "Returning to the Moon: the Science of Exploration." The three sections were generally organized via topics including missions and payloads, volatiles and ISRU, and dust. Each section hosted 7-8 talks allowing for 20-30 minutes of collaborative discussion with the presenters. In addition, there was a poster session associated with the oral sessions that showcased several additional abstracts.

TRAIN

SSERVI values the development of the next generation with the same importance as the core research. For over a decade a foundational element of SSERVI has been training the next generation through a host of research-centered activities. At its heart, SSERVI research solicitations encourage postdoctorate and graduate student funding and undergraduate participation as a core part of the greater research team.

In addition, SSERVI has a history of funding one or two postdoctorate positions at a time through the NASA Postdoctorate Program (NPP) via SSERVI Central; these positions are designed to bridge the work of 2-3 SSERVI teams and thus accelerate collaborative inter-team activities.

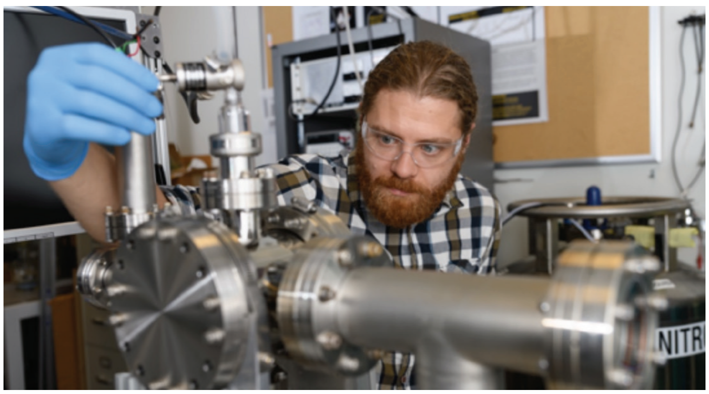
SSERVI Central has also supported graduate student field training efforts at both Barringer Crater (Arizona) and the Sudbury Impact Structure (Ontario). In 2020, SSERVI also established the practice of involving students and postdoc as Co-Chairs for sessions at major meetings to facilitate networking in times of the pandemic. SSERVI Central provides training to teachers (including lunar sample certification) and co-hosts and supports student challenge events for all ages, and is proud to support the dissemination of materials for the sight-impaired through its series of “Getting a Feel” tactile books. The following section highlights selected contributions from the Central Office in support of training the next generation in 2020.



Barringer Crater. Photo credit: Alex Gerst/NASA

NASA Postdoctorate Program Summaries

The NASA Postdoctorate Program (NPP) has proven to be fruitful in mentoring early-career researchers while cultivating cross-team collaboration, and SSERVI anticipates funding an additional postdoc in 2021. Micah Schaible completed his NPP in 2020 after contributing to ground breaking research on electrostatically charged dust, while postdoc Midhun Menon continues his work designing navigation and teleoperation algorithms for lunar exploration. Below is a brief report on their research activities.



Micah J Schaible, SSERVI NPP Fellow, Georgia Institute of Technology.

Low Energy Electron and Electrostatic Charged Dust Grain Interactions with Biomolecule Films

Solar and cosmic radiation on the surface of the Moon and other airless bodies in space can damage biologic molecules and poses a very real threat to future astronauts. Additionally, radiation can erode dust grains on an atomic level, modify molecular bonds, and cause electrostatic charging through emission of secondary electrons. Irradiated grains can themselves damage biologic tissues and sensitive electronics through electrostatic discharge. Understanding the potentially harmful effects of dust and radiation is crucial to any sustained exploration of the Moon, asteroids, or other airless bodies. As a SSERVI Central funded NPP, I spent the last two years working on three separate research projects related to various aspects of ionizing radiation interactions with airless bodies and biomolecules.

As a SSERVI Central funded NPP, Schaible summarized the last two years working on three separate research projects related to various aspects of ionizing radiation interactions with airless bodies and biomolecules:

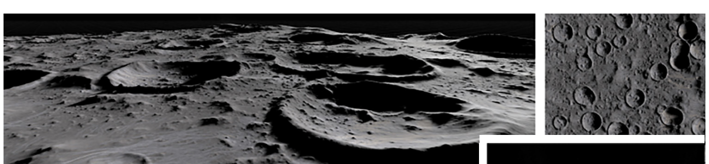
1) Together with the REVEALS, IMPACT, and LEADER (formerly DREAM2) SSERVI teams, I studied how electrostatically charged grains interact with molecular film analogs of lung cell wall membranes (DPPC) and novel conducting polymer materials being developed by the REVEALS team. A novel high vacuum system was constructed at Georgia Institute of Technology that can electrostatically charge grains either through tribocharging or exposure to electrons from a hot filament source. Interactions of charged grains with both biomolecule films and conducting polymer materials was studied by either placing the grains directly on top of the sample and charging them, or by dropping the charged grains onto the samples. The interactions of charged dust grains with the DPPC films deposited on bare silica showed that the grains did not strongly adhere to the surfaces, but that discharge caused changes in the molecular bonding and film morphology. Additionally, experiments using a conducting polymer film showed that a moderate voltage potential could be applied to the conducting surface to readily remove tribocharged dust grains. Future work in collaboration with the SSERVI LEADER team will study irradiated grain surface reactivity, grain discharging kinetics, and surface passivation through exposure to various low-pressure gas environments.

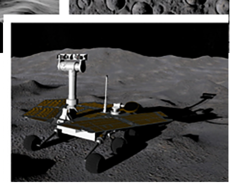
2) An opportunity which originated outside of SSERVI during the first year of the NPP program has led to a recently published study relevant to the amino acid (aa) content of primitive asteroids. Analyses of the enantiomeric excesses (ee) of aa found in a growing number of meteorites tend show a preference for the L-enantiomer. A largely unexplored mechanism for the formation of ee in meteorites is stereoselective interactions between spin-polarized electrons (SPE) and chiral molecules, termed spin dichroism. In collaboration with researchers at the Advanced Photon Source (APS) synchrotron, we showed that SPE ejected from magnetized cobalt substrates interact differently with chiral L-histidine depending on the electron helicity (Schaible, M. J., et al. 2020). Although much work remains to be done, these results suggest that magnetic materials in asteroids could contribute to ee observed in some meteorites. Future work in collaboration

with researchers from the SSERVI LEADER team (Jamie Elsila Cook) will correlate results with analyses of chiral molecules found in primitive meteorites.

3) During SSERVI NPP funded travel to the 2019 DPS conference, I was able to meet and establish a collaboration with scientists from the JAXA Mars Mission eXplorer (MMX) mission team. Based on work begun during my PhD studies, I provided the Mass Spectral Analyzer (MSA) instrument team with estimates of the secondary ion sputtering rates around Phobos and Deimos that were included in an article recently submitted to the journal Earth, Planets, and Space (Yokota, Shoichiro, et al.). Future work will further extend these estimates to understand how secondary ion sputtering rates vary based on the incident ion type, surface composition, and exposure time. Furthermore, in collaboration with researchers from the SSERVI LEADER team (Menelaos Sarantos), the secondary ion densities will be determined as a function of altitude and orbital position of Phobos and Deimos around Mars.

Midhun S. Menon, SSERVI NPP Fellow, University of Colorado, Boulder.





Lunar Telerobotics Research Using Virtual Reality Simulators

Midhun S. Menon[1], Michael E. Walker[2], Daniel Koris[2], Dan Szafir[2], and Jack Burns[1], [1]Center for Astrophysics and Space Astronomy, University of Colorado, Boulder (Email: midhun.sreekumar@gmail.com), [2]ATLAS Institute, University of Colorado, Boulder.

Space missions of the future involve complex in-situ construction activities and will increasingly rely on robotic systems to safely and efficiently achieve their objectives. Designing and testing such robotic systems for space exploration is still an open challenge given the limited scope of field analogs, the only available, viable option. Virtual planetary environment simulators provide a fast, flexible, and cost-effective alternative to field analogs for generating datasets for algorithm design/testing, operations planning, operator training, and mission mock-ups. At the University of Colorado Boulder, we have developed a scalable and modular simulation framework that generates photometrically accurate lunar virtual environments based on Digital Terrain Models (DTM) generated from the Lunar Reconnaissance Orbiter (LRO)-Narrow Angle Camera (NAC). The framework renders the environment using the Unity game engine and tightly integrates with the Robotic Operating System (ROS) to simulate the robots interacting with the environment. We model the robotic systems as ROS nodes, which accept inputs from the virtual environment via multiple simulated sensors like mono/stereoscopic cameras, LIDAR, and Inertial Measurement Unit (IMU).

We have incorporated dynamic tessellation to the terrain, making the simulator memory-efficient yet capable of adding detailed simulations like wheel tracks, which often act as an additional input to vision-based navigation algorithms. The FARSIDE mission proposal, which envisions constructing a 128-node distributed radio telescope array on the lunar far side, is our case study. We have consistently achieved eight frames per second with the simulator from multiple trials, which guarantees low visual lag performance. We are using the simulator to compare Simultaneous Localization And Mapping (SLAM) navigation algorithms. ORBSLAM2 and MIT Kimera were incorporated into the platform, and a comprehensive comparative study and failure analysis will be carried out on these and other publicly available visual-odometric SLAM algorithms. The end results will be used to design navigation and teleoperation algorithms specific to the Moon.

LUNGRADCON

The 10th annual Lunar and Small Bodies Graduate Forum (LunGradCon 2020) was held virtually on July 1st and 2nd, 2020. This meeting was organized for students, by students, and featured a gathering of over 90 graduate researchers and early career scientists from over 40 different institutions – LGC's largest to date. Participants logged in not just from all over America, but also 10 other countries including France, Malaysia, Canada, Belgium, and Tajikistan.

During the conference, 25 students presented their research in a low-stress, friendly environment, gaining experience presenting to a technical audience while receiving feedback from their peers. Panels with SSERVI leadership and Next Generation Lunar Scientists and Engineers allowed students to ask questions about life after grad school, funding, and various other career topics.

As a primary goal of LunGradCon's is to foster networking among students, social hours were also hosted with attendees put into digital rooms of 5-7 people. This allowed students to meet the other young researchers that they will be working with as they pursue their careers in future exploration science.

More information and abstracts from the 2020 LunGradCon can be found at impact.colorado.edu/lungradcon/2020. Students interested in attending LunGradCon 2021 are encouraged to send an email to lungradcon@gmail.com to receive registration information when it becomes available.

Teacher Training

SSERVI Central has an ongoing collaboration with the Astronomical Society of the Pacific and their annual Summer Institute, providing training for K-12 teachers. Normally conducted in person at the ASP headquarters in San Francisco, this year's program was conducted virtually. SSERVI Central's Brian Day presented an introduction to using NASA's Solar System Treks portals as part of this year's program.

SSERVI continues to develop and support the NASA Astromaterials group at JSC. As a certified trainer for U.S. teachers who would like to borrow Apollo Moon Rocks and Meteorites from the NASA Educational Disk Program, SSERVI planned and executed two Teacher Workshops in conjunction with the Journey Through the Universe program. Over 25 U.S. teachers learned how to handle and secure these national treasures while highlighting SSERVI research in lunar and meteoritic studies. We effectively increased our certification program to once a year with options to add additional workshops as requested within NASA Ames U.S. education territory as designated by NASA HQ.

We successfully submitted a signed contract between NASA Astromaterials and SSERVI acting as Principal Investigator to use NASA lunar material to build and manage five new NASA Touchstone displays. In support of the education and public engagement activities of SSERVI Teams, SSERVI Central developed and produced an educational Regolith Simulant Mass Flow display tool to help teach planetary soil mechanics.

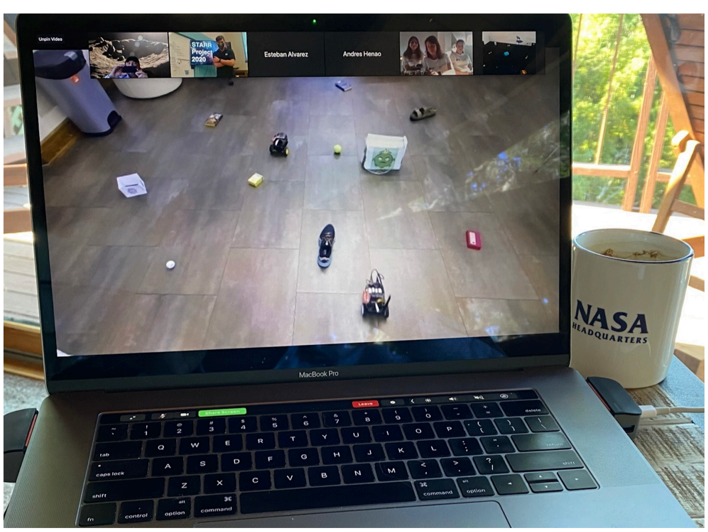
SSERVI trained Navajo Nation teachers in preparation for NASA's OSIRIS-Rex mission. This year SSERVI collaborated with Microsoft Xbox on porting SSTP Mapping technologies into the gaming platform to find innovative ways of reaching and inspiring the public.

Robotics

SSERVI continues to support and develop relationships with RoboRave International and the Regolith Mining Competition (RMC) to encourage students and teachers to bring robotics into the home and classroom. Robotic competitions are the culmination of student training in coding, engineering, and in developing regolith mining strategies.

This year, working with Kennedy Space Center's annual College Robotics Mining Competition and RoboRave International during COVID was especially challenging, but none-the-less SSERVI was able to expand relationships and support thru COVID lockdown, and served at national and international Robotics Competitions as a keynote and invitational speaker. Working with RoboRave International for the past 4 years SSERVI has observed and consulted in the development of an online robotic programing education platform called RoboSensei, which has increased online robotics learning and competition participation. SSERVI participated in bi-monthly programs with many virtual planning meetings, speaking engagements, competition judging, and support for Robotic education worldwide. Mayor Riku Miyamoto of Kaga City in Japan increased his support of RoboRave activities with the launch RoboSensei, and contracted to pay for every student in Kaga City to use this new platform to compete in a “Mayors Challenge” open to all students worldwide. Kaga City will host the next World Competition Event on July 16, 2021, which will be the first ever World RoboRave Robotic Competition.

SSERVI has also increased involvement with mentor college students in collaboration with the Systems Health Analytics, Resilience, and Physics modeling (SHARP) laboratory in the Intelligent Systems Division at NASA Ames Research Center. SSERVI worked closely with the NASA Ames SHARP lab to provide education outreach virtually to teachers and students worldwide. Through the efforts of RoboRave International and Inquiry Facilitators Inc., we helped develop a new Students & Teachers Assisting Real Research (STARR) program. Our pilot program has proved successful and has garnered the attention and future participation of Intel, Sandia Lab, and Spark Fun Electronics, who have all agreed to support this new mentor program.



Virtual meetings with Mayor of Kaga City Japan to plan an international robotics education program and competition.

INSPIRE

Engaging the public in the excitement of NASA's mission is a critical part of SSERVI's charter. SSERVI's public engagement efforts are centered around inspiring the next generation to learn about exploration science, and informing the public of what NASA and its partners are planning for future human exploration of the Moon and beyond. Public engagement is accomplished at SSERVI both through its Central office and the SSERVI teams, which are funded to enable the science activation, citizen science, and public engagement ecosystems that NASA has created. Teams are expected to implement activities furthering Science, Technology, Engineering, Art, and Math (STEAM) engagement. A summary of each team's public engagement efforts is included in their respective team reports.

SSERVI Central is involved in a wide variety of activities including: making public lectures and providing and staffing exhibits at many scientific, educational and public; visiting schools with activities for students, teachers, and under-served communities training teachers in key activities, and working with citizen scientists to provide input to various programs such as the Global Fireball Network. As part of these activities, SSERVI Central looks for opportunities to inspire disadvantaged groups including, but not limited to, the sight impaired, the Navajo Nation, and Pacific Islander communities. The following section highlights selected contributions from the Central Office in support of inspiring the public in 2020.

"You don't go to the Moon without capturing the hearts and minds of the public"
- Brian Day

Photo credit: Jordan Steranka/unsplash

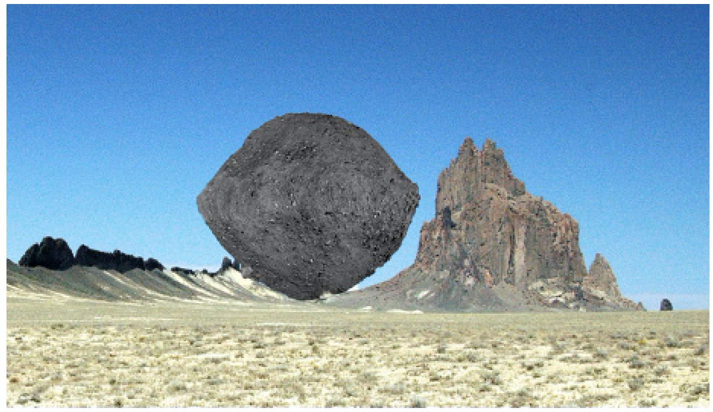
Classroom Visits

SSERVI visited more classrooms and certified more teachers in 2020 than any other year, due to working closely with NASA Ames outreach activities, Apollo 50th anniversary activities, and in helping support the new DKIST Solar Telescope in Maui. SSERVI visited over a dozen classrooms before the COVID shutdown in late February, sharing hands-on activities with lots of Astromaterials and rocks from space, including a rock from the Moon brought back by Apollo 17 Astronauts, and NASA Lunar and Meteoritic Education Sample Disks. Together we discussed basic planetary soil mechanics in compliment to the student's current studies of pebbles, sand, silt, and rocks, and also what we can learn from these samples in preparation for Artemis.

NASA's Science Mission Directorate and the National 4-H Council have partnered to make "Mars Base Camp" the topic for this year's annual 4-H STEM Challenge, with anticipated participation by 280,000 – 1,700,000 4-H members. At the request of SMD, SSERVI Central produced a video providing an introduction to Mars as well as its past and future exploration. SSTP leads Brian Day and Emily Law were featured in a live, online Q&A session for the program, hosted by 4-H.

Screen capture of live Q&A session hosted by 4-H.

Continuing and building upon a relationship with the Navajo Nation going back to the planning of the LCROSS mission, SSERVI is conducting a series of online classroom presentations throughout this school year for elementary and middle school students in the Gallup McKinley County School District. Our collaboration this year has taken on special urgency as this underserved community was hit especially hard by the COVID-19 pandemic. Students learned to use NASA's Bennu Trek and Ryugu Trek portals in conjunction with the OSIRIS-REx sample collection and Hayabusa2 sample return events. They studied upcoming Solar System exploration missions as well as made plans to conduct observations of astronomical events. Sessions are highly interactive with students taking half of each session for intensive Q&A.



SSERVI Graphic comparing the asteroid Bennu with the Navajo landmark Ship Rock.

SSERVI collaborated with the University of California Riverside's Department of Astronomy in their Cosmic Thursday's public lecture series. SSERVI Deputy Staff Scientist, Brian Day, presented a talk, "The Moon to Mars and Beyond: Our Future in Space," which was streamed live to audiences in North America, South America, Europe, Asia, and Australia.

Journey Through the Universe, Big Island, Hawaii

In partnership with NASA and Gemini observatory, SSERVI staff (Soderman, Day, Minafra) participated in the 16th Annual "Journey thru the Universe" program. This exceptionally popular and successful program of astronomy and space science outreach on Hawaii's Big Island, with special emphasis on reaching underserved native populations and homeland schools, has now become especially critical in light of heightened attention to diversity, equity, and inclusion and to the controversy associated with the TMT project on Mauna Kea. This year scientists visited over 300 classrooms in Hilo, Hawaii. SSERVI was instrumental in expanding this program to include classrooms on Maui through the new partnership with the Inouye Solar Telescope (DKIST), the world's largest solar telescope, as part of the National Solar Observatory. Brian Day and Joe Minafra conducted the NASA Apollo Lunar Samples and Meteorites Certification Workshop for 12 educators (Maximum workshop size) at the DKIST Science Support Center, and also trained and certified teachers in Maui to borrow NASA Astromaterials for use in their classrooms. In total SSERVI presented to students in 25 classrooms (various grade levels), gave two public lectures at the University of Hawaii at Hilo, and conducted two educator certification workshops.

SSERVI supported the 16th annual Journey Through the Universe program with scientists from around the world visiting over 300 classrooms in the Hilo, Hawaiʻi.

On Saturday-Feb 29, Brian Day and Joe Minafra conducted the NASA Apollo Lunar Samples and Meteorites Certification Workshop for 12 educators (standard workshop size) at the DKIST Science Support Center.

Brian Day and Joe Minafra under the Inouye Solar Telescope (DKIST), the world's largest solar telescope. SSERVI partnered with Inouye Solar Telescope (DKIST) the worlds largest solar telescope to train and certify teachers in Maui to borrow NASA Astromaterials for use in their classrooms.

International Observe the Moon Night

International Observe the Moon Night is sponsored by NASA's Lunar Reconnaissance Orbiter mission and the Solar System Exploration Division at NASA's Goddard Space Flight Center, with many contributors. Andrea Jones, Public Engagement Lead for NASA Goddard's Solar System Exploration Division and NASA's Lunar Reconnaissance Orbiter, is the Director of International Observe the Moon Night. This is an annual event where people come together with fellow Moon enthusiasts to learn about lunar science and exploration, take part in celestial observations, and honor cultural and personal connections to the Moon. This year, International Observe the Moon Night occured on September 26th, when the first-quarter Moon offered excellent evening observing--especially along the terminator (the line between night and day), where shadows enhance the Moon's cratered landscape.

SSERVI and SSTP have supported this event for many years, This year, SSERVI and SSTP created a series of Moon Maps depicting the Moon as it would appear for observers in the northern or southern hemispheres. These maps identified telescopic objects, lunar maria, and human landing sites (all six Apollo landing sites were visible that night!). The lunar landforms were highlighted in a video tour of the night's prominent observing targets streamed to a global audience on NASA TV. Additional programs were presented in streams for the Chabot Space and Science Center and MSFC/US Space & Rocket Center.

Artwork created by SSERVI's Jennifer Baer in support of International Observe the Moon Night. This internationally celebrated event featured sharable art templates created by SSERVI that are now in use by astronomy clubs around the world.

Photo credit: Amit Sharma

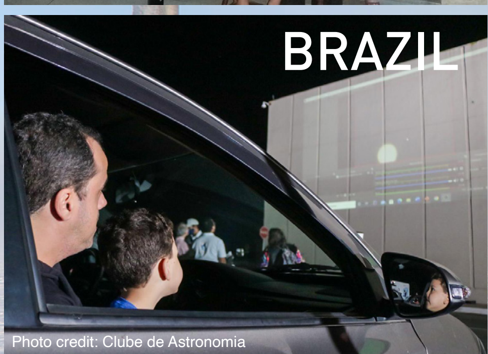
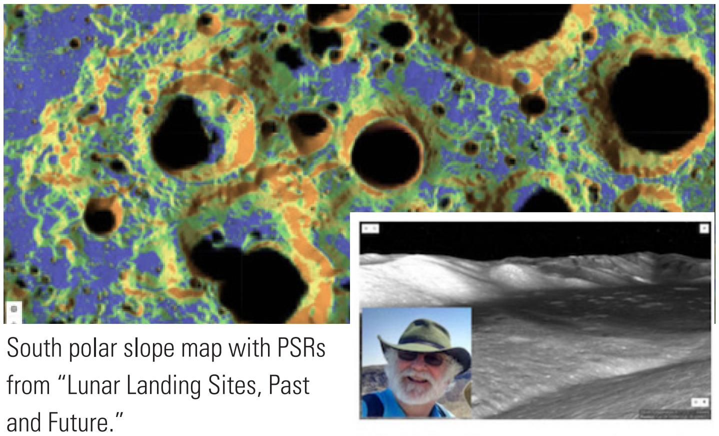


Photo credit: Clube de Astronomia

Researchers participating in International Observe the Moon Night at the Amundsen-Scott South Pole Research Station. Photo credit: Zach Tejra.

NASA Night Sky Network

SSERVI enjoys a long-standing collaboration with NASA's Night Sky Network, a nationwide coalition of amateur astronomy clubs bringing the science, technology, and inspiration of NASA's missions to the general public. In support of this effort, SSERVI Deputy Staff Scientist, Brian Day, presented a webinar, "Lunar Landing Sites, Past and Future." The webcast was viewed live by members of 141 different amateur astronomy clubs belonging to the NASA Night Sky Network.



South polar slope map with PSRs from "Lunar Landing Sites, Past and Future."

Brian Day presenting "Lunar Landing Sites, Past and Future."

Joe Minafra with Apollo Astronaut Al Worden at the Space Station Museum in Novato CA. SSERVI reunited Al Worden with lunar specimens originally brought back to Earth aboard his Apollo 15 Mission.

Braille Books

After an increase in interest from international embassies and outside groups for additional distribution in 2021, SSERVI funded and developed new "Getting a Feel" books for the blind with NASA HQ: an "Earth Science" book, an upgraded "Mars" book, a "50th Anniversary of Getting a feel for Lunar Craters" book, a "South American Eclipse" book, and an "Earth Day" one-page tactile in support of the sight impaired. Many international embassies have applauded our books for the blind and are using them to promote collaboration and support for their blind communities; this year our books were selected for a new permanent exhibit on display at the United Nations Headquarters building in Vienna. SSERVI is committed to this underserved community with this unique offering, and by promoting and encouraging blind and visually impaired participation in STEM careers, including some opportunities at NASA.

CONNECT

Working virtually – bridging geographical gaps to create collaborative teams that can thrive despite the distance separating their members – was an experiment for NASA years ago, but through SSERVI and other efforts it is now becoming more mainstream. Facilitating multiple, distributed teams working together on new, interdisciplinary science and exploration efforts is an essential part of SSERVI, but going beyond that and getting teams to truly collaborate across a heavily distributed network is where the real magic occurs. Virtual collaboration platforms – video and beyond – allow the sharing of ideas and information between disparate collaborators working towards a common goal. SSERVI Central's Tech team produces numerous virtual meetings, develops tools and integrates technologies that facilitate remote collaboration, and are recognized throughout NASA and the community as experts in their domain. Production of these meetings, ranging from the relatively small SSERVI Executive Council to conferences with hundreds of attendees, is a skill set garnered only through experience in a wide variety of settings, using a multitude of tools. SSERVI Central has provided insight and guidance to numerous Agency organizations and teams to increase the awareness and effectiveness of collaboration technologies.

In addition, the Tech team keeps a pulse on the latest state-of-the-art computer technology, actively researching, reviewing, and testing new tools, to find those best suited for each use case. Being located in Silicon Valley in close proximity to tech companies has fostered commercial partnerships, opportunities to beta-test and evaluate the latest collaborative tools, and has helped NASA keep a finger on the pulse of technological innovations.

Photo credit: Robert Simmons/NOAA/NASA

IT Infrastructure

Integration and implementation of virtual technologies is becoming more important at a time when the world is more virtually connected than ever before. SSERVI's Tech Team has supported virtual presentations, large conferences, webinars, workshops without walls, seminar series, and group-to-group and person-person meetings. SSERVI implements and integrates high-fidelity video conferencing, real-time meeting and communication platforms, websites and dynamic web applications, online communities, social networks, shared databases, data visualization applications, and mobile devices.

In addition, they address any problems that arise with the technology, and proactively work to remove barriers to collaboration by imparting the science teams with knowledge they need for any virtual collaboration media selected, so they understand how to use the technology and can perform their tasks efficiently with

lower frustration levels. This way, technology-mediated collaboration between virtual team members can be carried out seamlessly via the best communication tools available.

SSERVI Virtual Collaboration

For years, the annual SSERVI-hosted NASA Exploration Science Forum (NESF) has helped bridge and foster a multidisciplinary community with the goal of further enabling science and exploration. And for years, the success of these events has had little to do with the quantity of attendees, whether in-person or virtual. At the core of any successful event is the people; the ability for people to share, and feel seen, heard, and connected. From distinguished scientists to students, government to corporate leaders, and educators to enthusiasts, the NESF has revolved around the people within the planetary science and exploration communities.

In 2020, the public health and safety landscape experienced an unparalleled shift due to COVID-19. For many organizations, this meant that professional conferences would be canceled. For SSERVI, years of experience in producing hybrid in-person and virtual events enabled our team to adapt and deliver a community-centric Virtual Forum, as well as the many other events. The primary goal was to enable effective communication, collaboration, and networking capabilities to the attendees, all of which required making the technology layer as transparent as possible. And it all revolves around the user experience.

Event Production in 2020

SSERVI Central's Tech Team led the production and delivery of 69 events with over 725 presentations that were broadcasted live and made available for on-demand playback, usually within 24 hours. This valuable service makes important information widely available to the community; in 2020 SSERVI events had over 85,000 live-stream views and 13,265 views of recorded sessions. Of these, 44 were in direct support of SSERVI's domestic Teams while 15 events supported SSERVI affiliated organizations both inside and outside of NASA. SSERVI continues to receive praise for its multimedia content delivery and technical production capabilities.

Some of the main events included:

1. The 2020 NASA Exploration Science Forum, which produced 88 recorded presentations with 14,476 live views and 3,289 on-demand playback views.

2. The Lunar Surface Science Workshop which was a series of 6 separate events covering topics related to lunar surface science. There were 174 presentations recorded over 8 days, which included 28,964 live views, and 3,846

Event Production in 2020-continued

views of the recorded content. These events culminate in the development of a summary document with community input for NASA leadership to reference as they build future planetary science programs.

3. The 2020 Annual Meeting of the Lunar Exploration Analysis Group recorded 44 presentations with 6,690 live views and 1,777 on-demand playback views.

4. SSERVI produced the live broadcast and streaming of the 22nd and 23rd Meetings of the NASA Small Bodies Assessment Group. The two multi-day events produced 63 recordings that accrued a total of 3,117 live views and 156 on-demand playback views.

5. The European Lunar Symposium had 90 presentations, viewed by 13,352 live and 220 on-demand playbacks.

6. Other support included: CLASS/CLSE 2020 Spring Seminars and CLASS/FSI Seminars, Exploration and Origins Colloquium, Lunar Exploration Assessment Group Missions and Instruments Virtual Workshop, the 38th meeting of the Mars Exploration Program Analysis Group, LEAG/SSERVI Joint virtual meeting, Virtual Workshop Series on the Integration of Life Sciences in Space, Artemis III Science Definition Virtual Town Hall Meeting, Friends of Lunar Volatiles Focus Group, Equity, Diversity and Inclusion Focus Group, Analogs Focus Group, Dust, Atmosphere, and Plasma Focus Group, Payloads and Instrumentation Focus Group, Pre-proposal Conference for PRISM, TREX and NESS virtual Site Visits, and SSERVI Monthly Executive Council Meetings.

The Interface

The NESF website was the primary user interface for the all-virtual 2020 NASA Exploration Science Forum. At the forefront it is a responsive utilitarian design meant to usher participants to various Forum activities and make the presentation materials easy to access. The SSERVI Tech team designed a program page for the three-day event with quick links not only to the live sessions but also to presenter abstracts and on-demand playback links to recorded presentations. The platform was not device dependent, allowing for participation from a wide variety of phones, tablets computers, and/or operating systems.

Virtual Posters

Another critical element to the success of the virtual NESF were the poster presentations. It was more important than ever to give these poster authors, especially students, a platform for them to convey their research to as large of an audience as possible, while providing networking opportunities. The Tech team designed a virtual poster gallery equipped with asynchronous and real-time communication capabilities. A dedicated webpage was designed for each poster, where a digital version of the poster was made available to view and download. Additionally, poster authors were given the opportunity to upload a short overview video of their research that could be watched at any time. Finally, each poster was given a unique virtual meeting room where attendees could join and engage with the authors live during two, one-hour-long organized poster sessions. The inclusion of the virtual poster sessions was one of the most highly rated portions of the NESF this year.

Website Development

In addition to the SSERVI and NESF websites, the SSERVI Tech team provided website support to other organizations within SSERVI and the community. Below is a table listing the main websites supported in 2020.

Website	Description	URL
SSERVI	Defining the Institute while highlighting SSERVI research, related science, events/activities, and resources to the community.	sservi.nasa.gov
NASA Exploration Science Forum 2020	Home of the 2020 NASA Exploration Science Forum (NESF) where users found information on virtual logistics, registration, abstract submission, and on-demand playback of all live and archived presentations. NESF 2020 also featured a digital poster gallery that enabled live, dedicated sessions for each poster author to connect with attendees.	sservi.nasa.gov/nesf2020
SSERVI Awards	The SSERVI Awards website highlights past winners of the distinguished Shoemaker Medal, and the Wargo, Niebur, and Coradini Awards, while allowing the community to nominate candidates for the yearly distributed awards.	sservi.nasa.gov/awards
SSERVI Books	The SSERVI Books website was created to highlight the Institute's literary efforts, including books for the blind such as "Getting a Feel for Lunar Craters" and "Getting a Feel for Eclipses."	sservi.nasa.gov/books
European Lunar Symposium	The European Lunar Symposium (ELS) website provides users with logistics, registration, and abstract information related to this annual event.	els2020.arc.nasa.gov
Lunar Surface Science Workshop	A workshop providing an open forum for the presentation, discussion, and consideration of various concepts, options, capabilities, and innovations to advance scientific discovery on the lunar surface. The website provides a dynamic comment system to capture feedback from community members on various themes while making recordings of sessions available for on-demand playback.	sservi.nasa.gov/lssw
Artemis Science Definition Team	Providing community access to the Science Definition Team (SDT) report and virtual meeting, enabling users to provide comments and feedback.	sservi.nasa.gov/artemis-sdt
SSERVI Focus Groups	SSERVI hosts researcher-led Focus Groups on a wide variety of topics. Some groups host seminars and those recordings are archived on the website for on-demand playback.	sservi.nasa.gov/focus-groups
Lunar Exploration Analysis Group	SSERVI hosted the Lunar Exploration Analysis Group (LEAG) 2020 virtual meeting experience and created a website hosting a digital poster gallery with dedicated virtual poster rooms to facilitate networking amongst authors and participants. Additionally, live connection information and archived recording links were made available.	sservi.nasa.gov/leag2020

Websites developed and managed by SSERVI Central.

Start Date	End Date	Event Name
1/6/20	5/4/20	CLASS/CLSE Spring 2020 Seminar Series Webinars
1/10/20	10/2/20	Analogs Focus Group Meetings
1/14/20	1/16/20	22nd Small Bodies Assessment Group Meeting
1/28/20	1/28/20	Exploration and Origins Colloquium
1/28/20	3/24/20	CLASS/FSI Seminar Series Webinars
2/4/20	12/1/20	SSERVI Executive Council Meetings
2/7/20	2/7/20	LEAG Missions and Instruments Virtual Workshop
4/15/20	4/17/20	Mars Exploration Program Analysis Group #38 Meeting
5/11/20	10/13/20	Friends of Lunar Volatiles Focus Group Meetings
5/12/20	5/14/20	European Lunar Symposium 2020
5/20/20	5/20/20	LEAG/SSERVI Joint Virtual Meeting
5/28/20	5/29/20	Lunar Surface Science Workshop - Science Payload ConOps / Instrument Design & Compatibility
6/1/20	6/2/20	Small Bodies Assessment Group #23 Meeting
6/1/20	6/1/20	Virtual Workshop on the Integration of Life Sciences in Space - Introduction and Goal
6/9/20	6/9/20	Virtual Workshop on the Integration of Life Sciences in Space - technology and tools, and applications and detection
6/11/20	6/11/20	Virtual Workshop on the Integration of Life Sciences in Space - Tools we need on Earth and In Space
6/16/20	6/16/20	Virtual Workshop on the Integration of Life Sciences in Space - Artificial Intelligence, Machine Learning, Big Data, Data Mining: Fundamentals and Applications
6/18/20	6/18/20	Virtual Workshop on the Integration of Life Sciences in Space - Missions Concepts and Mission Campaigns – answering the science questions
6/23/20	6/23/20	Virtual Workshop on the Integration of Life Sciences in Space - Advocacy of RFPs, funding, and building the community
7/1/20	7/2/20	LunGradCon
7/8/20	7/10/20	NASA Exploration Science Forum 2020
7/15/20	7/15/20	SSERVI DAP Focus Group Meeting
7/16/20	7/16/20	SSERVI Payloads and Instumentation Focus Group Meeting
7/29/20	7/29/20	Lunar Surface Science Workshop - Volatiles
7/30/20	7/30/20	Lunar Surface Science Workshop - Samples
8/7/20	12/4/20	Equity, Diversity and Inclusion Focus Group Meetings
8/20/20	8/20/20	Lunar Surface Science Workshop - Dust & Regolith
9/14/20	9/16/20	LEAG 2020
9/30/20	9/30/20	Lunar Surface Science Workshop - Lunar Planetary Protection
10/22/20	10/22/20	Artemis III Science Definition Team (SDT) virtual TownHall
10/28/20	10/28/20	Lunar Surface Science Workshop - Lunar Surface Mobility
11/10/20	11/10/20	Pre-proposal Conference for PRISM
11/13/20	11/13/20	TREX Site Virtual Visit
11/19/20	11/19/20	Lunar Surface Science Workshop - Foundational Data Products
11/30/20	11/30/20	NESS Virtual Site Visit

Major events supported by SSERVI Central.

ACKNOWLEDGEMENTS

Many people contributed to SSERVI's successes in 2020. We would like to start by thanking our supporters at NASA Headquarters for their leadership, funding and guidance.

SCIENCE MISSION DIRECTORATE

Planetary Science Division: Dr. Lori Glaze, Dr. Sarah Noble, Dr. Amanda Nahm and Dr. Shoshana Weider,

Science Engagement and Partnerships Division: Kristen Erickson,

Astrophysics Division: Dr. Paul Hertz;

HUMAN EXPLORATION AND OPERATIONS MISSION DIRECTORATE

Advanced Exploration Systems: Mark Kirasich, John Guidi, Chris Moore,

SE&I: Dr. Julie Robinson, Dr. Jake Bleacher, Dr. Bette Siegel

OFFICE OF THE CHIEF SCIENTIST

Dr. Jim Green, Dr. David Draper.

We gratefully acknowledge continued support from NASA Ames Research Center. In particular, we thank Ben Varnell for his expert financial support, assisted by Michael Baumgarten and Delphina Turner; Barrie Caldwell,Bea Morales, and the NSSC teams for their outstanding procurement support; Chris Wilson for his expert IT support; and NASA Ames leadership.

We proudly acknowledge the key roles that SSERVI's teams, international partners, and many collaborators in the lunar community are taking on to enable Artemis and this next great adventure. We would like to particularly thank CAN-2 and CAN-3 teams for their infusion of exciting, new, innovative techniques and avenues of research. SSERVI is also grateful to work alongside so many international researchers helping to lead a global effort towards an expanded human presence in space.

SSERVI is proud to recognize the advances made by its Solar System Treks Project managed by Brian Day, with the technical team at JPL under the leadership of Emily Law.

SSERVI leadership gratefully acknowledges the work of its dedicated staff at SSERVI Central in accomplishing its many achievements.

Finally, we acknowledge all of our friends in the lunar science and exploration community. Your dedication, tenacity, and endurance have sustained the field through the lean years, reinvigorated the field today, brought forth a new generation of brilliant researchers and explorers, and taken us to the brink of humanity's sustained presence on the Moon and beyond.

Ad lunam, ad astra!

U.S. TEAM REPORTS

The SSERVI teams are supported through multi-year cooperative agreements with NASA (issued every 2-3 years) for long duration awards (5 years) that provide continuity and overlap between Institute teams. Each team is comprised of a number of elements and multiple institutions, all managed by a Principal Investigator.

CLASS **Center for Lunar and Asteroid Surface Science**
Daniel Britt, University of Central Florida, Orlando, FL

CLSE **Center for Lunar Science and Exploration**
David Kring, Lunar and Planetary Institute, Houston, TX

ESPRESSO **Exploration Science Pathfinder Research for Enhancing Solar System Observations**
Alex Parker, Southwest Research Institute, Boulder, CO

GEODES **Geophysical Exploration of the Dynamics and Evolution of the Solar System**
Nicholas Schmerr, University of Maryland, College Park, MD

IMPACT **Institute for Modeling Plasma, Atmospheres and Cosmic Dust**
Mihaly Horanyi, University of Colorado, Boulder, CO

ICE FIVE-O **Interdisciplinary Consortium for Evaluating Volatile Origins**
Jeffrey Gillis-Davis, Washington University, St. Louis, MO

LEADER **Lunar Environment and Dynamics for Exploration Research**
Rosemary Killen, Goddard Space Flight Center, Greenbelt, MD

NESS **Network for Exploration and Space Science**
Jack Burns, University of Colorado, Boulder, CO

RESOURCE **Resource Exploration and Science of OUR Cosmic Environment**
Jennifer Heldmann, NASA Ames Research Center, Mountain View, CA

REVEALS **Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces**
Thomas Orlando, Georgia Institute of Technology, Atlanta, GA

RISE2 **Remote, In Situ, and Synchrotron Studies for Science and Exploration**
Timothy Glotch, Stony Brook University, Stony Brook, NY

TREX **Toolbox for Research and Exploration**
Amanda Hendrix, Planetary Science Institute, Tucson, AZ

VORTICES **Volatiles, Regolith and Thermal Investigations Consortium for Exploration and Science**
Andy Rivkin, Applied Physics Lab, Johns Hopkin University, Laurel, MD

CAN-3 TEAMS

CAN-2 TEAMS

CAN-1 TEAMS

SSERVI U.S. TEAM EXECUTIVE SUMMARY REPORTS

CLASS

The Center for Lunar and Asteroid Surface Science (CLASS) team led by Dr. Dan Britt at the University of Central Florida studies the interaction between the surfaces of airless bodies and the space environment, exploration activities, and potential resource exploitation. Our research includes measuring and observing the physical and thermal properties of regolith material, observations of the mineralogy of primitive asteroids, the behavior of regolith in lunar and microgravity, the chemical reactions and reaction products that are part of space weathering, combined radar and optical characterization of asteroid surfaces, the cohesive forces on small asteroids including the interparticle forces and charging, analysis of the cohesive properties of meteorites, asteroids and bolides, development and launch of cubesats, and the use of regolith as a resource for construction, fuel, and life support consumables. One major focus is outreach to the NewSpace commercial community to provide the best science support for this innovative engineering startup sector. CLASS has several node-wide initiatives including on-line advanced planetary science education with six graduate-level seminar courses recorded for community access, the CLASS Exolith Laboratory which is the world leader in the development and production of lunar and asteroid regolith simulants, and the CLASS Planetary Landing Team which brings together the world's experts in rocket plume dynamics and surface interactions with the leaders of the growing commercial landing industry. CLASS is fundamentally an organization to bring the best science into the service of lunar and asteroid exploration. CLASS team members worked with graduate and undergraduate students at UCF and across member and external universities. Despite COVID restrictions, CLASS members were active in virtual outreach programs, public presentations, and presentations to the media about ongoing lunar and asteroid mission activities.

CLSE

The Center for Lunar Science and Exploration (CLSE) team led by Dr. David Kring at the USRA Lunar and Planetary Institute and NASA Johnson Space Center studies impact history and processes, geochemistry of regolith, including volatile components, and ages of regolith materials on the Moon and other airless bodies. The bulk of CLSE's work this year was devoted to the geology of the lunar south pole, physical processes that may have affected the distribution of volatile elements in that region, and options for landing sites and EVA for the Artemis program. CLSE determined that Shackleton crater was produced by an asteroid 1.5 to 1.8 km in diameter, hitting the lunar surface at 15 to 20 km/s. The team showed that the impact excavated a crater from two types of terrain: a crystalline terrain that may be a remnant of the lunar magma ocean and a layered terrain that appears to be a series of impact ejecta blankets deposited by nearby polar craters. CLSE also showed that ice within those types of deposits can affect the morphology of a crater and is, potentially, responsible to asymmetries in the morphology of the Shackleton crater rim. CLSE further showed that ballistic sedimentation processes that occur when ejecta blankets are deposited may have affected the distribution of polar volatiles. CLSE studied a half dozen landing sites on the rim of Shackleton crater and several other locations near the south pole. Options for walking EVAs within 2 km of a landing site and for lunar terrain vehicle traverses within 10 km of a landing site were explored. An assessment of bearing capacities in south polar sunlit regions was completed, which was used to evaluate rover trafficability in the Artemis exploration zone.

ESPRESSO

The Project for Exploration Science Pathfinder Research for Enhancing Solar System Observations (Project ESPRESSO) team led by Dr. Alex Parker at the Southwest Research Institute conducts a broad array of pathfinding investigations to identify novel techniques and technologies for enhancing the safety, efficiency, and scientific productivity of human and robotic exploration of the Moon and asteroids. In 2020, Project ESPRESSO continued to mature systems for remote active spectroscopy of lunar and asteroid materials, enabling flexible and high-throughput mineralogical analysis using a new optical system developed by our team. Our team prepared for our second campaign of reduced gravity flights with an ambitious slate of granular mechanics experiments that would provide important constraints on the dynamics of mass movement on the Moon and asteroids, critical for planning future surface operations. Further, the team implemented a suite of large-scale vacuum chambers for reduced gravity flights, enabling experimentation and hardware testing in relevant pressure and gravity environments. COVID-19 prevented our 2020 flight campaign from occurring, but the experiments and chambers are ready to go once international travel can resume. Team members tested a self-forming, self-healing network topology for a dense network of very low mass seismic sensor motes based on low-cost, off-the-shelf MEMS devices developed for terrestrial oil and gas exploration. These sensor motes and the mesh network concept could enable a 21st century version of the Apollo Active Seismic Experiment using landed mission activity as an active seismic source. Finally, the SSERVI-developed concept of magnetic regolith collection for asteroid surfaces was put to the test onboard a suborbital flight, where two free-flying sub-scale demonstrators of magnetized micro-landers collected and stored regolith in vacuum and microgravity. These tiny, robust, and extremely efficient free-flying regolith sampling systems could enable future asteroid sample return missions to safely and reliably collect samples from many sites across many asteroids, potentially making future returned sample libraries as rich as the meteorite collection or astronomical asteroid catalogs.

GEODES

The Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES) team led by Dr. Nicholas Schmerr at the University of Maryland uses multidisciplinary geophysical investigations to explore a suite of natural resources on the Moon and other airless bodies. Geophysical methods have been incredibly successful in identifying resources on Earth as they provide a means of characterizing and mapping the subsurface using data gathered on and above the surface. In our first full project year during 2020, the team collected new planetary analog datasets in a volcanic setting for future geophysical missions to the surface of the Moon and developed new tools for performing joint inversions across different geophysical datasets. Members of the team also showed, through models of the stress field around a lunar lava cave, that cracks are expected to develop over much of the floor and part of the roof of the tube, with failure of the tube materials more likely near the walls--an important constraint for future missions exploring tubes. The team performed modeling work on particle shaking in low gravity and simulations of how larger grains migrate through regolith, and used the results to understand the rock abundance on the surface of asteroid Bennu and characteristics of the OSIRIS-REX sample collection mission. The team amassed over 103 GB of geophysical data collected by precursory projects and has created a new searchable data depository and documentation that is designed to be a model for presenting field analog datasets to the scientific community. A new joint collaboration with members of the TREX team used Apollo seismic data to study how ground motion from moonquakes could pose a potential hazard to future mission infrastructure and astronauts.

ICE FIVE-O

The Interdisciplinary Consortium for Evaluating Volatile Origins (ICE Five-O) is a multidisciplinary team of researchers who are leaders in their field. Team ICE Five-O aims to resolve questions about the origins and interactions of volatile deposits on the Moon and other airless bodies by conducting innovative experiments, performing state-of-the-art sample analyses, modeling water-regolith reactions, and writing the manual on collection, curation, and analyses of cryogenic samples. Our efforts are focused at the intersection of science and exploration in order to address fundamental questions about the Earth-Moon system and extend a human presence in the Solar System. The Team P.I. is Jeffrey Gillis-Davis at Washington University in St. Louis. The ICE Five-O network of scientists incorporates domestic institutions across the USA (California, Hawaii, Maryland, Missouri, and Texas) and international partner institutions in Canada.

IMPACT

The Institute for Modeling Plasmas, Atmospheres, and Cosmic Dust (IMPACT) team, led by Dr. Mihaly Horanyi at the University of Colorado Boulder, studies of the effects of high-speed meteoroid impacts, plasma and ultraviolet (UV) charging, mobilization and transport of dust due to human/robotic activities, and natural processes, on the physical, chemical and geotechnical properties of regolith surfaces. They have continued the development of novel plasma and dust instrumentation for the lunar surface to resolve decades-old open questions about the origin of the lunar swirls and the horizon glow, based on their ongoing series of small-scale laboratory experiments. The IMPACT dust accelerator facility enables exploration of the effects of meteoroid impacts into icy surfaces, the development of new ways for in-orbit exploration of permanently shadowed regions, and the assessment of the accessibility of their volatile content for future ISRU needs. New experimental setups have been developed for the use of an electron beam to safely and efficiently remove dust from space suits--a critical element for mitigating dust hazards for any future human presence on the lunar surface.

LEADER

The Lunar Environment And Dynamics for Exploration Research (LEADER) Center for Space Environments is a modeling-lab-data center of excellence designed to answer the overarching question: "How does the highly-variable energy and matter in the inner heliosphere affect volatile stability, plasma interactions, dust migration, and surface micro-structure at the Moon, and how will this dynamic lunar environment change in response to human presence? As humans begin to establish a permanent presence on the Moon and use resources found there, they will need to be aware of the environmental challenges this creates – to understand the health challenges this may impose on our astronauts, as well as the effects explorers will have on the fragile lunar environment. Hazards to astronauts and critical systems include radiation damage, studied by LEADER's Fatemeh Rahmanifard (2020); extreme surface charging events including dielectric breakdown, or "sparking," in cold soil on the Moon studied by LEADER'S Andrew Jordan [Jordan, 2021]; and effects lunar dust will have on human health and mechanical systems. LEADER's Christine Hartzell chairs JPL's Lunar Dust Mitigation Science Definition Team. Finally, the nature and extent of the effect explorers and their systems have on the lunar environment has been explored by LEADER's Parvathy Prem who studied the effect of rocket exhaust on the lunar exosphere [Prem et al., 2020]. Explorers are exposed to space plasma and charged particle radiation, and this environment creates a human system plasma-charging hazard as well as a radiation human health issue. In the next year, the team will determine the amount of shielding required to protect human habitats against charged particle radiation under different solar cycle conditions.

NESS

The Network for Exploration and Space Science (NESS) team led by P.I. Jack Burns at the University of Colorado Boulder is an interdisciplinary effort that investigates the deployment of low frequency radio antennas in the lunar/cis-lunar environment using surface telerobotics. The purposes of these radio telescopes are cosmological and astrophysical measurements of neutral hydrogen at the end of the Dark Ages, during Cosmic Dawn, and at the onset of the Epoch of Reionization; radio emission from the Sun; and extrasolar space weather and exoplanets. NESS continues to advance instrumentation and a data analysis pipeline for the study of the first luminous objects (first stars, galaxies and black holes) and departures from the standard model of cosmology in the early Universe, using low frequency radio telescopes shielded by the Moon on its farside. The design of an array of radio antennas at the lunar farside to investigate the Dark Ages, Heliophysics, and Exoplanet Magnetospheres, is a core activity within NESS, as well as the continuous research of theoretical and observational aspects of these subjects. NESS keeps developing designs and operational techniques for teleoperation of rovers on the lunar surface facilitated by the planned Lunar Gateway in cis-lunar orbit. New experiments, using rovers plus robotic arms and Virtual/Augmented Reality simulations, are being performed to guide the development of deployment strategies for low frequency radio antennas via telerobotics.

RESOURCE

The Resource Exploration and Science of OUR Cosmic Environment (RESOURCE) team is led by Principal Investigator (P.I.) Dr. Jennifer L. Heldmann and Deputy P.I.s Dr. Matthew Deans and Dr. Alexander Sehlke at NASA Ames Research Center. RESOURCE is focused on enabling In-Situ Resource Utilization (ISRU) near the sites of robotic and/or human missions to enable sustainable and affordable exploration of the SSERVI Target Bodies. This year RESOURCE has developed a summary of the current state of knowledge regarding lunar polar volatiles and presented these results to the National Academies Committee on Planetary Protection in support of their study on the potential planetary protection issues for lunar exploration. RESOURCE is developing advanced mission capabilities such as a Virtual Mission Simulator System to enable rapid, collaborative operations for lunar resource exploration missions. Hardware testing has been conducted to evaluate potential contaminants released during lunar polar regolith heating. Volatiles and particulates are the two sources of contamination that will affect the requirements of a water cleanup system, and RESOURCE research has identified the requirement for filtration prior to electrolysis for ISRU. RESOURCE also leads development of next-generation planetary drilling systems with integrated scientific instrumentation to change the paradigm regarding subsurface sample handling and measurement on the Moon. RESOURCE is also deeply committed to sustained efforts to engage educators, students, and broadening participation among underrepresented groups, and has partnered with Howard University in Washington, DC to foster minority students' interest in STEM careers through direct and virtual experiences with NASA Subject Matter Experts (SMEs) of color.

REVEALS

The Radiation Effects on Volatiles and Exploration of Asteroids and Lunar Surfaces (REVEALS) team led by Prof. Thomas Orlando at the Georgia Institute of Technology investigates the condensed matter physics, materials chemistry and applied aspects associated with radiation-induced processes in regolith and man-made composite materials relevant to the exploration of near-Earth destinations. In 2020, the team refined the atomistic model for the formation, diffusion, transport and eventual polar trapping of water on the Moon and Mercury. The experimental results on several Apollo highland and mare samples provided the binding site energy distributions and general kinetic parameters for future models to simulate volatile formation via impact events. The sustained small scale micrometeorite impact events can produce water at a rate that can lead to a quasi-continuous source in the near surface region. Overall, water formation and release will occur for any solar system body or object that has thermal excursions above 350 K following or during proton irradiation. A laser-based micrometeorite accelerator has been constructed and tested to directly determine whether water and other volatiles such as methane form during impact of both highland and mare Apollo samples. Knowledge of water formation mechanisms, loss channels and diffusion coefficients have been integrated into a novel ISRU strategy that uses solar and microwave energy to extract volatiles from polar regions. The REVEALS efforts also involve the development and testing of novel polymer composites containing functionalized reduced graphite-oxide (rGO). These composites have high mechanical strength, high thermal and electrical conductivities, and appear to be resistant to ionizing radiation. 3-D printing of these and other polymers may be exploited to make "fabric" for spacesuits. In addition, EVA helmet display technologies and novel two dimensional meta-materials are being developed and tested as real-time passive radiation detectors. These materials and active dosimetry will eventually be integrated into spacesuits and hardware (i.e. helmets, etc.) for extra-vehicular and surface exploration activities. Overall, the REVEALS efforts are addressing many SMD and HEOMD objectives to help understand and minimize risks associated with radiation exposure during human exploration.

RISE2

The Remote, In-Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2) team led by Prof. Timothy Glotch at Stony Brook University uses advanced field, laboratory, modeling, and remote sensing techniques to enable the safe and efficient exploration of the Solar System and to maximize the science return from missions to airless bodies in the Solar System. In Year 1 of our work, we have made substantial progress towards our goals through (1) the continued method development and data acquisition of simulated asteroid environment infrared spectra with applications to the analysis of OSIRIS-REx Thermal Emission Spectrometer data, (2) near-field infrared (nano-IR) model development and data acquisition for carbonaceous chondrites, leading to a successful NASA LARS proposal to procure a nano-IR instrument at Stony Brook University, (3) software development and data analysis to enable the characterization of volcanic environments using field-portable scientific instruments, (4) software development for managing concepts of operations in the field and the use of augmented reality for field data visualization (5) synthesis and experimental space weathering of high-fidelity lunar analog regoliths, (6) reactivity, cytotoxicity, and genotoxicity tests of space weathered lunar analog materials, (7) hardware and methods development enabling microscale X-ray absorption fine structure (EXAFS) analysis of element valence states at the Argonne National Laboratory Advanced Photon Source, (8) scanning transmission electron microscope (STEM) analyses of space weathered and shocked grains from the asteroid Itokawa, returned by the JAXA Hayabusa mission, and (9), advanced X-ray absorption spectroscopy and STEM analyses, including nanometer-scale vibrational spectroscopy of chondritic insoluble organic matter. These scientific advances were supplemented by a robust public engagement plan and were made possible by the contributions of 29 undergraduate students, graduate students, and postdoctoral scholars.

TREX

The Toolbox for Research and Exploration (TREX) team, led by Dr. Amanda Hendrix of the Planetary Science Institute, had a productive year, even if things did not go according to plans due to the COVID-19 pandemic. The foundation of the TREX team work is the creation of an ultraviolet-to-mid-infrared spectral library of fine-grained materials measured under planetary conditions. Toward that goal, in the past year, laboratory work and analysis of the TREX terrestrial mineral samples wrapped up, and work on the meteorite samples began. Numerous results from TREX studies on lunar and asteroid studies were reported in publications and in meetings throughout the year, and TREX analyses led to exciting instrument and mission proposals. The TREX public engagement program took full advantage of the virtual milieu, engaging with students and communities in the online environment. A highlight of the year was the TREX site visit, held--virtually--on November 13.

VORTICES

The VORTICES team spent its final full year pursuing projects of opportunity and preparing for the end of the project with the remaining funds. While the COVID-19 pandemic upset specific plans for in-person work and travel, the team adapted to the world in which we found ourselves. VORTICES supported important lunar research, including detection of water and other ices near the lunar poles using microwave radiometer data and study of an observed impact during a lunar eclipse. Additional work was done to update our well-established lunar lighting and communications calculation software and make it more user-friendly for HEOMD users. Asteroid research done by the team centered on explorations of a taxonomic system rooted in the 2—4 μm spectral region. Support was also used for manuscript preparation, including for white papers submitted to the Decadal Survey panels, and for support of VORTICES team members sitting on community group steering committees and the Exploration Science Forum Scientific Organizing Committee.

Center for Lunar and Asteroid Surface Science (CLASS)

Daniel Britt

University of Central Florida, Orlando, FL

CAN-3 TEAM

1. CLASS Team Report

1.1. Daniel Britt: CLASS P.I.: UCF

The CLASS Exolith Lab is the de facto world-wide standard for ISRU, lunar, Martian, and asteroid related engineering. The Exolith lab has shipped 4618 Kg of simulant to 275 customers worldwide in 2020. The expertise on the CLASS Landing Team has resulted in multiple collaborations with CLIPS and other potential commercial providers (many of which are CLASS partners) for lunar landers. CLASS continues to prioritize partnerships with 18 NewSpace commercial companies with the objective of making the best planetary science support available to this growing industry. CLASS services to this sector include the Exolith Lab, the CLASS Landing Team, and acting as a science team for NewSpace startups. Two graduate students defended during this period: Leos Pohl and Wesley Chambers.

1.2. Adrienne Dove: Deputy P.I.: UCF

Dove worked with graduate student Wesley Chambers, who defended his PhD, on microgravity regolith-plume interactions using an experiment apparatus in the Center for Microgravity Research Drop Tower. The Gas-Regolith Interaction Testbed (GRIT) creates controlled bursts of air into a simulant bed, and the resulting video data is analyzed to qualitatively and quantitively constrain gas-regolith interactions. We have observed unique phenomena (Figure 1), which will be used in comparison work with Masten Space Systems tests, and to guide models for plume-regolith interactions on low-gravity planetary surfaces. Dove and students also have progressed on work with the Electrostatic Regolith Interactions Experiment (ERIE), which will be used to characterize dust grain charging and behavior in microgravity when it flies on Blue Origin New Shepard suborbital flights in 2021.

Figure 1. Ejecta created due to a gas jet impingement on spherical beads in the GRIT microgravity drop tower experiment.

Dove worked with Co-I Metzger, FSI Engineer Mike Conroy, and students to develop the prototype EjectaSTORM instrument. This instrument, which uses laser to illuminate and discern the properties of dusty plume dynamics, was tested on a Masten Space Systems tethered and point-to-point rocket flight in December 2020.

1.3. Christopher Bennett: Deputy P.I.: UCF

Bennett has been working with graduate students (K. Slavicinska and B. Ferrari) to complete the space weathering ultra-high vacuum chamber in his UCF laboratory (Figure 2). This chamber covers the visible, near-IR, and mid-IR spectral ranges using diffuse reflectance spectroscopy comparable to remote observations to study powders, slabs, ices, and mixtures of ices/powders, which can be temperature controlled from 10-1000 K and subjected to radiation from keV electrons and UV photons for space weathering studies. Bennett and students (K. Slavicinska, R. Havel, R. Cantelas, and S. Swiersz) performed preliminary space-weathering experiments in

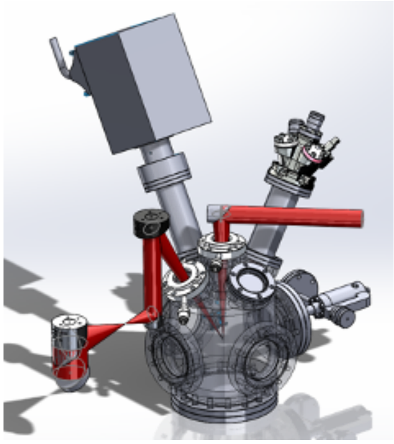


Figure 2. SolidWorks drawing of the optical layout of the space weathering chamber.

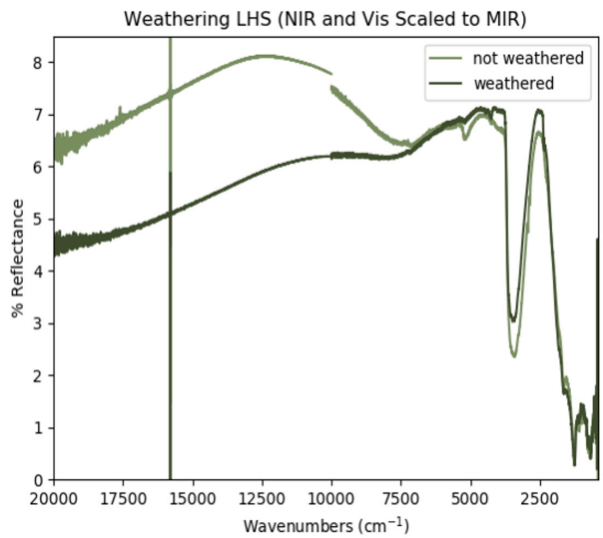


Figure 3. Spectra of Exolith Lunar Highland Simulant (LHS) before and after being subjected to simulated space-weathering.

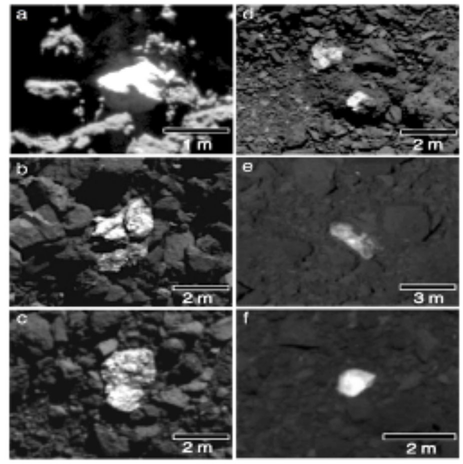


Figure 4. Close-up images of the surface of asteroid Bennu from the OSIRIS-REx spacecraft, showing several high-albedo boulders which have spectral features consistent with those from Vesta.

collaboration with Richard Blair (UCF; CLASS collaborator) on olivine and lunar and meteorite simulants (Figure 3). He has also been working with Amanda Hendrix and Melissa Lane (TREX) and Tim Glotch (RISE2) to determine an appropriate reference standard covering the full optical range that can be used for our spectral measurements.

Bennett continues to collaborate with T. Orlando & B. Jones (REVEALS) and D. Britt, S. Seal & L Pohl (CLASS) to correlate thermo gravimetric analysis (TGA), differential scanning calorimetry (DSC), and temperature programmed desorption (TPD) of simulant and extraterrestrial materials. Bennett and students have been working with our international collaborators at Lille (France) to study carbonaceous meteorites using Raman spectroscopy as well as high-resolution two-laser desorption mass spectrometry (HR-L2MS). We anticipate that we should have two papers from this work in 2021.

Bennett was awarded time at the Advanced Light Source (Berkely, CA) to perform nanoIR measurements on carbonaceous meteorites, but this has been delayed until 2021 due to COVID-19.

1.4. Humberto Campins: Co-I: UCF

Campins has published five high-impact publications this year. Of these publications, maybe the most surprising discovery is "exogenic basalt on asteroid (101955) Bennu." Campins had predicted the existence of "xenoliths" (material originating in a different parent asteroid) on the surface of Bennu based on similarities between Bennu's orbit and that of the unusual meteorite Almahata Sitta. This publication confirms those prediction and shows that the collisional evolution of asteroids is much more complex than anticipated. In fact, the sample that OSIRIS-REx delivers to Earth in 2023 may also contain pieces of asteroid Vesta! Figure 4 is an image (from Della Giustina et al. 2020a) with the six large basaltic boulders identified in this study.

> "Our analysis of boulders on the surface of the asteroid Bennu, using images taken from the OSIRIS-REx spacecraft, reveals several high-albedo boulders which are spectrally consistent with the delivery of Vesta-material to the surface of the asteroid."

1.5. Josh Colwell: Co-I: UCF

In 2020, improvements were made to the COLLIDE-3 microgravity impact experiments to improve the performance and triggering on Virgin Galactic suborbital flights. The experiment was delivered to Virgin Galactic for flight in December 2020, but during the flight, the rocket's motor shut down prematurely and thus the experiment did not run. We anticipate a flight in early 2021.

At the Center for Microgravity Research, we continue to explore the adhesion of small regolith particles to larger particles simulating ejecta blocks and secondary impactors. Graduate student Stephanie Jarmak (PhD Spring 2020) had developed SPRING-E, which uses a spring to simulate the rebound of a projectile off of an asteroid or planetesimal surface following a low-speed impact. This year, we have developed a new variation of this experiment, dubbed PULL-E, that provides for a constant velocity removal of the impactor from the target, which more closely replicates a microgravity collision and rebound.

Colwell and graduate student (I. Rivera) developed a model based on the Mercury N-Body code (Chambers, 1999) to simulate ejecta blasted off the surface of the Moon due to rocket exhaust on launch and landing. The simulation includes the gravitational effects of the Moon and the Earth, allowing for long-term tracking of particles in cislunar space. Launches and landings can be simulated at any location on the surface of the Moon with full control over the ejecta velocity distribution. Particles will be tracked to determine collision probabilities with surface assets as well as lunar-orbiting spacecraft.

1.6. Yanga Fernandez: Co-I: UCF

Fernandez and grad student Jenny Larson continue to study the dynamical behavior of ejecta liberated from the surface of an asteroid. Here, the Rebound N-body simulation package has been augmented to produce a new code entitled "RED" (Rebound Ejecta Dynamics), which was detailed in a submitted paper. The test-case discussed in this paper involves ejecta from an impact on an asteroid in a binary system – highly relevant to the upcoming DART mission (Figure 5).

Fernandez and grad student Mary Hinkle continue to characterize the thermal and scattering properties of the regolith of NEA (433) Eros. A recent result is that thermal parameters suggest that the effective roughness at mid-IR wavelengths is different than that at near-IR wavelengths, which likely is related to the size and fractal nature of the regolith grains. Fernandez continues to work with multiple institutions (including Arecibo Observatory) to obtain near-IR spectra of objects that are observed with the radar facility at Goldstone (and, until recently, at AO). The characterization of the NEAs in the infrared enhances the interpretation of the radar echoes and the scattering properties.

1.7. Kerri Donaldson Hanna: Co-I: UCF

Donaldson Hanna has been setting up an environment chamber capable of simulating near-surface conditions of airless bodies. This chamber is connected to an FTIR spectrometer, making it possible to collect spectral measurements under a range of environmental conditions. Grad student Vanessa Lowry has written Python code that uses a linear least squares algorithm to unmix thermal infrared spectra into its mineral constituents. She has applied this to laboratory measurements of a suite of fine particulate physical mixtures and meteorites that are analogs of primitive asteroids. Her results show that linear least squares algorithms are not accurate at modelling mineral abundances of fine particulate materials, shown in Figure 6.

1.8. Sudipta Seal: Co-I: UCF

Seal is performing measurements of physical properties of minerals, simulants, and meteorite samples (differential scanning calorimetry, thermogravimetric analysis under both ambient atmospheric conditions and vacuum, X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and Brunauer-Emmett-Teller (BET) surface area analysis). An example of this work is shown for the observed

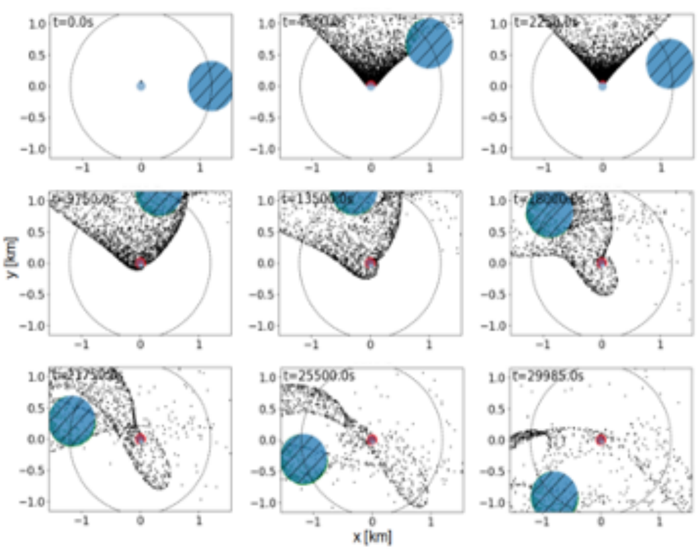


Figure 5. Snapshots from a simulated evolution of ejecta (black dots) liberated from an asteroid's moon in a DART-like impact scenario. The small blue dot is Dimorphos, and the large blue, hashed circle is Didymos.

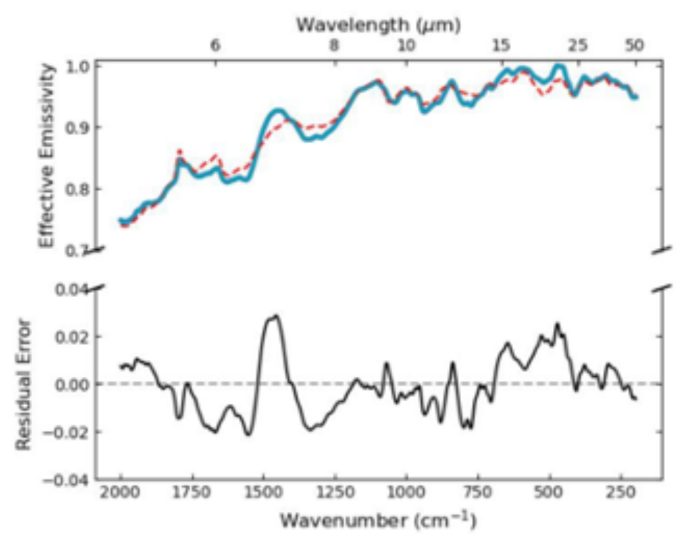


Figure 6: Linear least squares unmixing results for a fine particulate mixture volumetrically dominated by San Carlos olivine. The blue line is the lab spectrum of the mixture and the red-dashed line is the modelled spectrum. The bottom plot shows the residual between the lab and modelled spectrum.

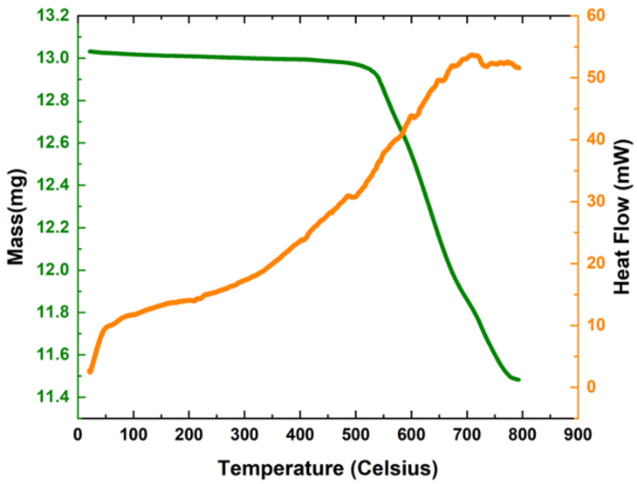


Figure 7: Example Differential Scanning Calorimetry of antigorite, showing dehydration and phase changes (confirmed by XPS, XRD).

mass losses of antigorite (Figure 7). Seal has also been investigating Regolith-Plasma interactions by exposing pressed coupons of CLASS simulant to an Argon plasma gun, inducing Spark Plasma Sintering (SPS). We have demonstrated that new phases of materials along with increased levels of SiO2 and Al2O3 are produced after exposure of simulant to the Ar gun using XRD. These studies can help understand the mechanical properties of regolith and benefit landing operations which may use such materials (e.g., for launch/landing pads).

1.9. Phil Metzger: Co-I: UCF/Florida Space Institute

Metzger has been involved in extensive CLASS Landing Team work on a number of plume related projects. These include Masten Space Systems, SpaceX, NASA KSC, NASA MSFC, and Ceres Robotics as well as several others. He is supporting plume research for the NASA Human Landing System and working with A. Dove on Ejecta STORM. These projects have resulted in the hiring of two post-docs and three undergrads to support plume research. He is also working with MECO Robotics and Puerto Rico college-level robotics competitions, ice mining thermal extraction and beneficiation, and Puerto Rico robotics landing pad construction competition.

1.10. Kevin Cannon: Co-I: UCF/Colorado School of Mines

Cannon spearheaded new research into understanding lunar water ice deposits, with a focus on the stratigraphy and nature of the deposits. This requires the use of Monte

> CLASS research will help determine which lunar cold traps are the most accessible targets to provide support for the upcoming ARTEMIS and CLPS lunar programs.

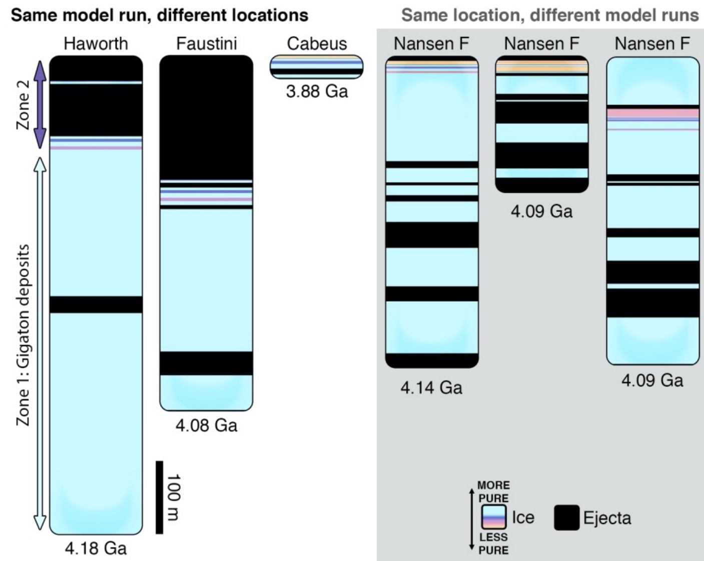


Figure 8. Selection of lunar craters with different ice/ejecta stratigraphies predicted by Monte Carlo modeling.

Carlo techniques and an improved understanding of water delivery over the entire history of the Moon. Figure 8 shows the results of this modeling effort, which suggests that for some lunar craters, billions of tons of ice may be buried under thick layers of dry regolith; as a result, the surface ice detected from orbit may be decoupled from the subsurface ice itself. To better understand lunar ice deposits, in-situ study by robots and humans is necessary in some of the larger cold traps at the poles. In a new study by K. Cannon and D. Britt, an automated approach was used to determine the accessibility to wheeled vehicles for the 59 largest cold traps at the north and south poles of the Moon. It was found that 55/59 of these can be readily accessed without exceeding difficult slopes, opening the door to future exploration (Figure 9).

1.11. Dan Scheeres: Co-I: University of Colorado

Scheeres has published several papers related to asteroid science and has contributed to several asteroid-related missions, which include Janus, DART, and OSIRIS-REx. In "Cohesive Regolith on Fast Rotating Asteroids," Scheeres and Co-author P. Sanchez model the migration of cohesive

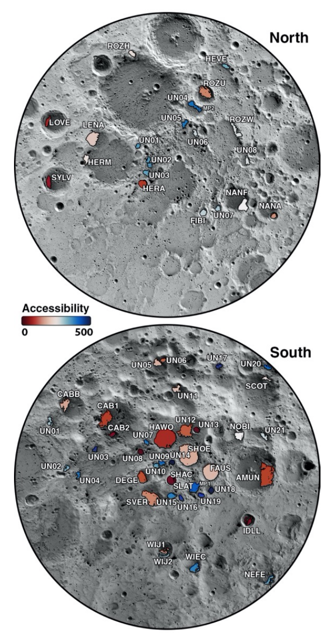


Figure 9: Accessibility levels of 59 lunar cold traps.

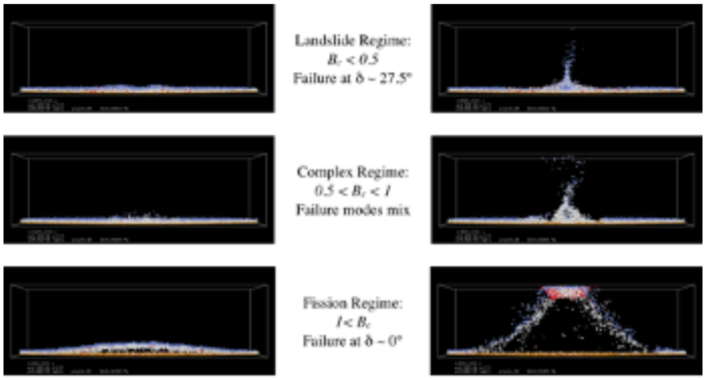


Figure 10: Simulations showing different failure patterns as a function of increasing bond number. Figures on the left show the system at the start of failure, and on the right show the system after most of the failure has occurred at the given spin rate. The bond number, B, is the cohesive force acting on a grain divided by its gravitational weight.

regolith on the surface of an otherwise monolithic or strong asteroid. They find that under an increasing spin rate (e.g., due to the YORP effect), regolith is preferentially lost across certain regions of the body, dependent upon the regolith cohesive strength (Figure 10). The derived scaling law can be used to determine whether observed asteroids could retain surface regolith grains of a given size. They discuss implications of this for the interpretation of spectral observations of small asteroids and boulder migration on large asteroids.

> "We have found that material can be lost and redistributed at different latitudes on small and large asteroids as a function of spin rate and the cohesive strength of the regolith."

1.12. Cyril Opiel: Co-I: Boston College

Opeil et al. (Meteoritics & Planetary Science 55, 2020) reports heat capacity, thermal conductivity, thermal diffusivity, thermal inertia, and linear thermal expansion of five CM2 carbonaceous chondrites (5 ≤ T ≤ 300 K). Measurements of linear thermal expansion of the samples reveals a negative thermal expansion (NTE) behavior at T ~ 235 K. The origin of the NTE in CM2 meteorites is likely due to the temperature-dependent interaction between transverse and longitudinal vibrational components between the octahedral and tetrahedral layers of the hydrous phyllosilicates that dominate the mineralogy of these meteorites. The importance of this NTE behavior is that if an asteroid surface is made of CM2 material and it passes through this temperature range (200-250 K), the rocks would be prone to cracking if they experience repeated temperature changes. The fracturing of surface rocks on an asteroid (such as the asteroid Bennu, the target of the OSIRIS-REx Mission) could significantly decrease the thermal conductivity of this material, which results in a reduced thermal inertia of the asteroid surface and is what the mission has observed.

Opeil also made thermo-physical measurements of lunar meteorites. Heat capacity, thermal conductivity & linear thermal expansion of six lunar meteorites (NWA 5000, NWA 6950, NWA 8687, NWA 10678, NWA 11421, and NWA 11474) were measured from 5-300 K. Linear thermal expansion measurements in the range of 200 > T > 300 K show a relatively small and typical thermal expansion for composite material. In the range of 5 > T > 200 K we note a negative thermal expansion (NTE) behavior that differs slightly for each sample (Figure 11). These data are important for exploration of the permanently shadowed regions on the Moon.

1.13. Mark Boslough: Co-I: University of New Mexico

Boslough has been developing methods and running simulations to model the Meteor (Barringer) Crater impact as a hybrid airburst/impact event, comparing identical simulations of crater formation with and without atmospheric effects, focusing primarily on distribution of ejecta using fragment tracking. These simulations include both 2D axial and 3D rectangular symmetry to

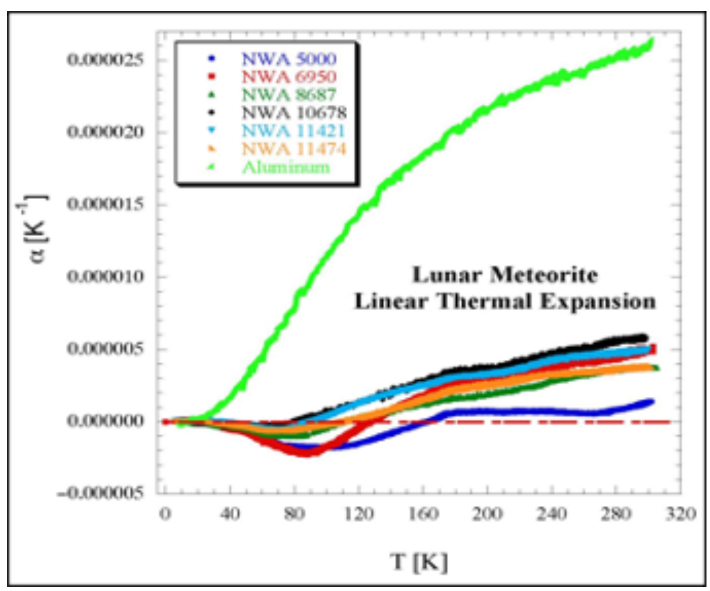


Figure 11: Linear thermal expansion coefficient (α_L) vs. T measurements of six lunar meteorites indicate a low temperature negative thermal expansion (NTE) below 200 K. Aluminum is shown as a reference. Error bars are smaller than the symbols.

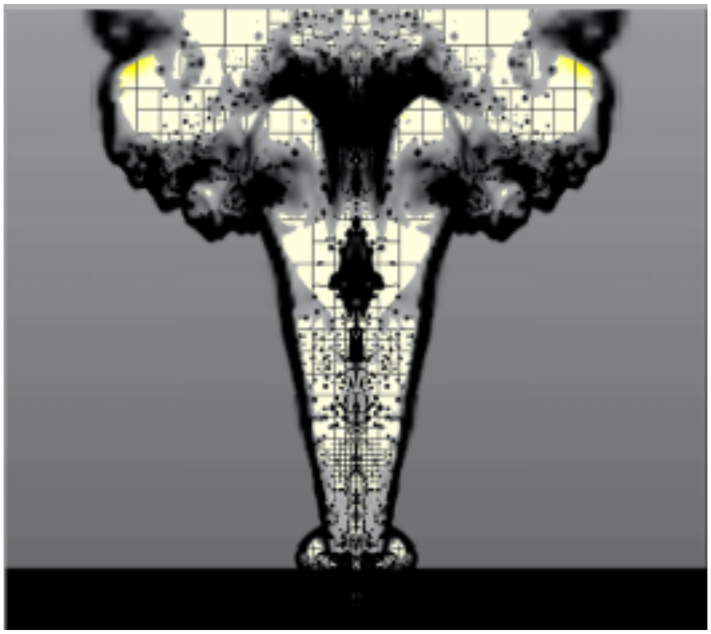


Figure 12: An adaptive-mesh simulation of the Meteor (Berringer) Crater forming event, which was the result of a hybrid airburst/impact event. This example is a high ratio example, one second after impact. The box is 5 km wide.

explore the effect of the wake on distal ejecta velocity as a function of direction, applying methods used to model nuclear weapons effects to model blast wave propagation from airburst and impact events (Figure 12). Generating transfer functions will allow determination of the global distribution of mass and momentum and seismic coupling due to reentry of the highest-velocity ejecta from large impact events (e.g., Chicxulub, Ries, Zhamanshin, and the Australasian tektite-forming event). This accounts for impact latitude and planetary rotation. Through CLASS and SSERVI, M. Boslough has begun several successful scientific collaborations, which include: i) Meteor Crater seismic survey (with D. Schmitt, J. Delph, B. Johnson, B. Schmandt, and G. Collins), ii) Science-based Meteor Crater impact illustrations (with D. Kring (CLSE) and D. Davis), iii) Tektite formation, cratering mechanics, and airbursts (with C. Koebert), iv) Modeling global connections including K/Ph impact and Deccan Traps trigger (with W. Alvarez and M. Richards), and v) Zhamanshin and contemporaneous impacts and global environmental effects (with J. Garvin).

> "This work modeling airburst/impact events is a result of new collaborative efforts and access to computer facilities that would not have been possible without SSERVI and CLASS."

1.14. Paul van Susante: Co-I: Michigan Technical University

van Susante has spent the majority of this year commissioning and testing the Dusty Thermal Vacuum Chamber (DTVAC) designed for lunar environment simulation, which has received additional funding through a NIAC LPMO Phase II grant. The DTVAC (Figure 13) has a usable volume of 50 x 50 x 70 inches, which can be filled with 3000 lbs of simulant, and can be cooled to -196 °C, heated to 200 °C, as well as reach a vacuum level of 10-6 Torr. The chamber has two 10" viewports, as well as numerous smaller ports, data and power feedthroughs. The Planetary Surface Technology Development Laboratory at MTU also features an enclosed sandbox (14 x 6 x 1 ft in size). These testbeds are ideal to study and develop autonomous robotic rovers within realistic lunar environments.

1.15. Robert Mueller: Co-I: Kennedy Space Center/ Swampworks

Each year, R. Mueller organizes the NASA Robotic Mining Competition (RMC) at Kennedy Space Center. The competition is for university-level students to design and

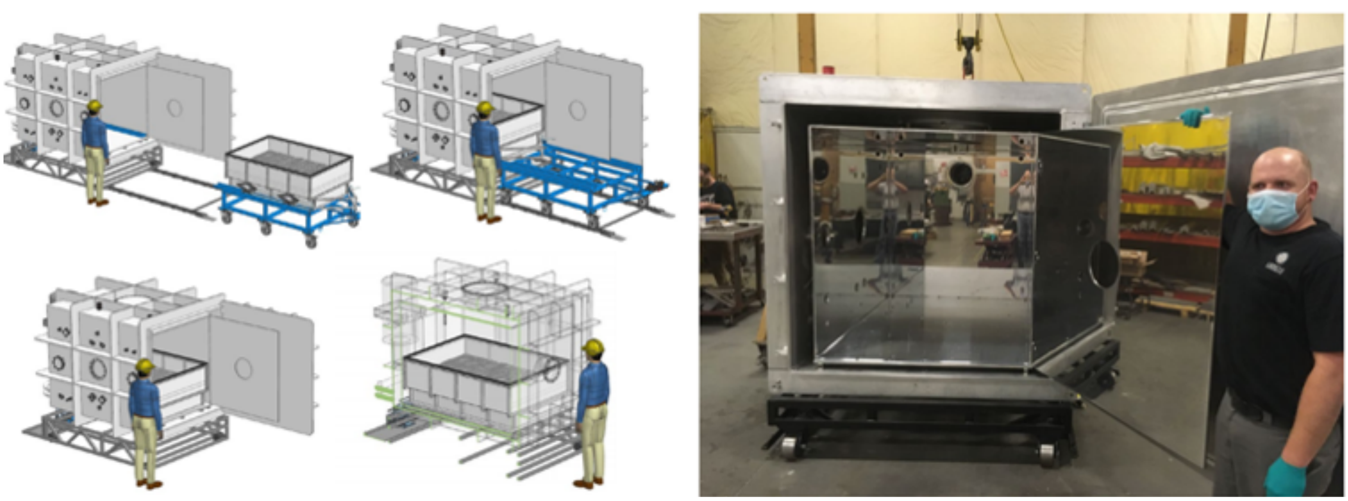


Figure 13: (Left) rendering of the loading procedure for the simulant bed into the DTVAC. (Right) the actual DTVAC chamber at MTU.

build a mining robot that can traverse the challenging simulated lunar terrain. The mining robot must simulate an off world, in-situ resource mining mission. Due to COVID-19 the RMC on-site final competition at KSC was not held in 2020, however the systems engineering papers from each university were still evaluated. A new competition regolith simulant arena has been built at the KSC Center for Space Education (CSE) which is indoors, so that weather risk in future events has been eliminated.

The University of Central Florida, Aerospace Engineering Department Senior Design Project class has been sponsored by NASA KSC Swamp Works and CLASS, providing technical expertise to create a scaled, cheaper functioning engineering model of a NASA regolith excavation robot called Mini-Regolith Advanced Surface Systems Operations Robot (Mini-RASSOR; Figure 14). Students were responsible for writing control software and computer simulations for lunar regolith and water ice mining operations while the Mini-RASSOR mechanical engineering model was provided by NASA Swamp Works in collaboration with CLASS. The project is in its third year and now has a robotic platform which can be 3D printed by the students for implementation of software and testing operations. The mechanical design that was developed with SSERVI support is being licensed to universities and educational institutions by the NASA KSC Tech Transfer office.

This effort has expanded under the leadership of Mike Conroy at Florida Space Institute (FSI). Students from the following universities are working on various aspects of a Research & Education (RE) RASSOR version:

- University of Central Florida
- University of South Florida
- Florida Polytechnic
- Technical University of Munich, Germany

Figure 14: 3D-Printed Mini-RASSOR Robotic mining excavator.

RE-RASSOR is a more generic version of Mini-RASSOR, running the UCF developed EZ-RASSOR software. Prior to Fall 2020, EZ-RASSOR software projects were performed, completed and tested in a simulation environment (ROS GAZEBO), with hardware projects completed in a piece-wise manner. Since Fall 2020, all the projects are focused on integration into physical systems by the end of the respective terms.

The NASA KSC CLASS team is supporting an effort for Plume Surface Interaction (PSI) effects for lunar missions modeling and landing/launch pads materials testing activities. A specialized two-phase CFD program (GGFS) is being used to explore SpaceX Starship PSI effects. Mitigations for these effects are also being studied. CLASS expertise is being used on a consulting basis. Additionally, various materials coupons were tested in a relevant environment under a Masten Space Systems Oxygen/Methane rocket engine to establish feasibility of using them to construct a lunar landing and launch pad (Figure 15).

NASA directly benefits from robotic competitions and multi-year student capstone projects. The innovative concepts students develop can result in clever real-world ideas and solutions which can be applied to actual excavation payloads on ISRU missions.

1.16. Paul Abell: Johnson Space Center

Abell is continuing to support the ongoing study for identification of low-deltaV mission targets among the NEO population as part of the Near-Earth Object Human Space Flight Accessible Target Study (NHATS). This is led by the Center for Near-Earth Object Studies (CNEOS) at JPL with NASA GSFC and NASA JSC support. He is actively

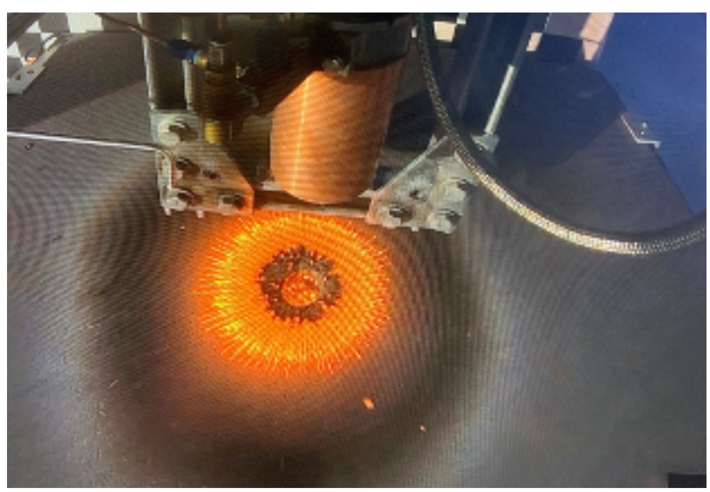


Figure 15: Testing an ablative material coupon under a Masten Space Systems rocket engine.

assessing and identifying potential NEA targets that could be promising for future missions and requesting additional observations of these targets from the observing community. As part of his work on Artemis-related activities with respect to human exploration, Abell is continuing to support the EVA tools development for human destinations with a particular focus on Artemis with respect to deployment of instruments and sample collection activities. He is also providing feedback on possible sample collection/curation objectives that are relevant for the agency, and particularly to ARES interests with respect to retuning volatile samples from the Moon's south polar region for the Artemis program.

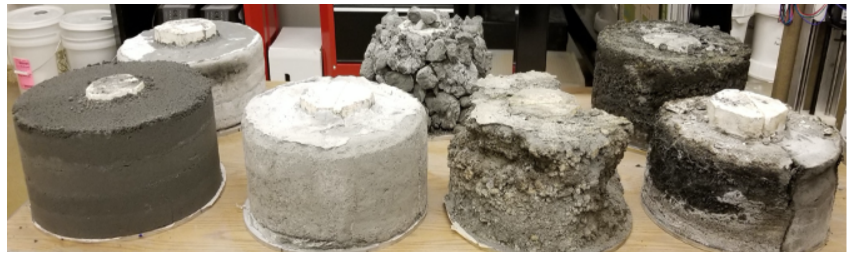


Figure 17: Examples of simulant 'cakes' prior to and after exposure to various optical mining processes.

Abell is also actively involved with research pertaining to the Hermes ISS payload/facility. He is aiding the transition of the Hermes ISS payload/facility and attempting to identify the full capabilities of the facility to inform future Artemis goals and objectives to relevant stake holders (e.g., Orion, HLS, Gateway, etc.). He is also facilitating discussions with NASA's Space Technology Mission Directorate about Hermes use as a platform to investigate adherence of lunar dust to various material under microgravity conditions. Cross-correlation to similar materials to be flown on the 19D CLPS Regolith Adherence Characterization (RAC) experiment.

1.17. Robert Macke: Co-I: Vatican Observatory

This year, in collaboration with D. Britt, C. Opeil, and G. Consolmagno, R. Macke has continued measuring the thermal properties of meteorites as a function of temperature from 5-300 K. Macke performs additional immersion heat capacity measurements with samples submersed in liquid nitrogen. He has also performed hypervelocity impact studies at the NASA Ames Vertical Gun Range (Figure 16) in collaboration with G. Flynn, M. Strait, and D. Durda. Of chief interest here is how the porosity of meteorite targets influences the momentum multiplication factor (β) which should be accounted for in collisions involving low-density asteroids. R. Macke is investigating the relationship between porosity and shocks within ordinary chondritic meteorites with A. Ruzicka, J. Friedrich, and others, where he contributes microporosity measurements to these studies. Lastly, R. Macke also makes porosity measurements of the carbonaceous chondrite Almahata Sitta, in collaboration with C. Goodrich, M. Zolensky, and others.

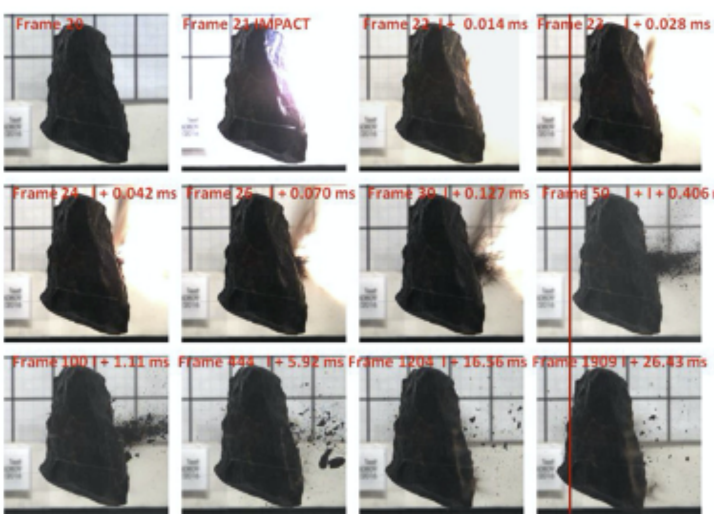


Figure 16: A 1/16th inch Al projectile traveling at 4.9 km/s is impacted into 352g of NWA 4502 meteorite. A high-speed camera (~71,000) frames/sec records the impact sequence and recoil of the meteorite.

"Our studies have shown that the porosity of a body considerably affects the resulting momentum transfer during asteroid collisions."

1.18. Joel Sercel: Co-I: TransAstra

TransAstra developed an optical mining test bed (OMTB) to perform experiments on various CLASS simulants. TransAstra partnered with CLASS on three different LuSTR proposals. Preliminary tests were performed on a CI-simulant, partially funded under a NIAC Phase 2 program. The sample was exposed to 200 W/cm2 for 14 mins, 36 secs, and we achieved an excavation rate of 5.0 kg/hr (a 10% improvement over our previous efforts). Overall, the OMTB run was successful; the improved debris catcher managed to catch most of the debris despite more spread than expected. Figure 17 shows an example of a simulant cakes before and after exposed to the OMTB. TransAstra has also made significant progress on the Mini Bee Asteroid Mining Technology Demonstrator (P.I.: Sercel), which is supported by both CLASS and NIAC Phase 3 funding and is planned for launch in 2023.

1.19. Kris Zacny: Co-I: Honeybee

Unfortunately, Honeybee Robotics (HBR) is very much hardware/test related and has been drastically affected by COVID-19, thus most of the CLASS-related research has been delayed for the time being.

1.20. Robert Jedicke: Co-I: UH

Jedicke has been working on calculations of the water return rate to cis-lunar space from ultra-low delta-V asteroid targets as well as optimization of round-trip spacecraft trajectories to synthetic ultra-low-density delta-V asteroid targets.

1.21. Noemi Pinilla-Alonso: Co-I UCF

The study of the primitive bodies in the Solar System continues to pay special attention in the inner main belt, as the origin of NEAS with potential for ISRU. In 2020, we forward the preparation of the primitive asteroids spectroscopic survey (PRIMASS) archive to be uploaded to the NASA-PDS node of small bodies. We also performed analysis of the Chaldaea and Sulamitis families in the NIR (Arredondo et al. 2021)¸ and of the extended family of primitive bodies, to be published in 2021. Also, we took advantage of the discovery of the 2I/Borisov, the first interstellar comet discovered in 2019, to perform observations in the optical and near-infrared wavelength domain and in the radio frequencies, with the Arecibo telescope. Results were presented at the 2020 virtual meeting of the Division for Planetary Sciences and published in de Leon et al, 2020 (for the VNIR) and in preparation as Ceballos-Ortiz et al. 2021, for the radio domain. Finally, Pinilla-Alonso worked with Britt and Dove on the program for a CLASS graduate seminar for the spring of 2021 that will display the actual science at the Arecibo observatory and its historical achievements.

1.22. Clive Neal: Co-I Notre Dame University

COVID-19 has adversely affected planned grad and post-doc recruiting. Working with a new company, MHI, on Helium-3 mining and fusion power. Introductions from CLASS have made possible collaborations with Masten, TransAstra, University of Michigan on three LuSTR proposals. Also working with Boeing on their Lunar Terrain Vehicle.

1.23. Cassandra Runyon: Co-I: College of Charleston

C. Runyon and D. Hurd have been designing and developing a new tactile book for middle-school students. The book highlights Earth environs using NASA satellite data from the Scientific Visualization Studio (https://svs.gsfc.nasa.gov/Gallery/index.html) and Earthdata (https://earthdata.nasa.gov/). The expected completion date is May 2021. The distribution of tactile books worldwide has been remarkably successful, this year more than 200 tactile books were sent to 16 different regions across Chile (Figure 18), and more than 150 in Argentina.

Figure 18: Tactile South American Eclipse book in use in Chile.

> "CLASS and SSERVI have been distributing tactile books to educators and libraries – so far, we have distributed over 12,000 tactile books worldwide."

2019 and 2020 eclipse books distribution in Chile:		
National Science Ministry - Explora Program	National Inclusion Services (Senadis)	Giant Magellan Telescope (GMTO)
Las Campanas Observatory	AURA (Tololo & Gemini South Observatory)	ALMA Observatory
ESO (La Silla and Paranal Observatorie)	Chilean Astronomical Society (SOCHIAS)	Núcleo de Astronomía, Universidad Diego Portales
Centro de Comunicación de las Ciencias, Universidad Autónoma	Museo Interactivo Mirador (MIM)	Planetario de la Universidad de Santiago
Instituto Milenio de Astrofisica (MAS)	Corporación Cultural de Coquimbo	Centro Interactivo de Ciencias, Artes y Tecnología (CICAT)
Liceo Abate Molina de Talca	Agrupación Astronómica Sur	Colegio San Sebastián Akivi de Isla de Pascua
Planetario de Isla de Pascua	Fundación EcoScience	AstroBVI
Museo Marítimo Nacional	Agrupación Visión Futuro	

2. Inter-team/International Collaborations

2.1. RESOURCE

K. Cannon is working with RESOURCE members on projects related to lunar polar ice and its effects on terrain features.

2.2. ICE FIVE-O

K. Cannon is working with ICE Five-O members, analyzing potential landing sites in lunar cold traps.

2.3. CLSE

M. Boslough has been working with David Kring (CLSE) and Don Davis (space artist) to produce science-based Meteor Crater impact illustrations.

2.4. TREX & RISE2

C. Bennett is working with A. Hendrix, M. Lane, and T. Glotch on refining appropriate reflectance standards to use over the visible, near-IR and mid-IR ranges for spectral measurements in the space weathering chamber.

2.5. REVEALS

Continuing collaboration with REVEALS: Dan Britt, Leos Pohl, Sudipta Seal, and Chris Bennett are collaborating with Thom Orlando and Brant Jones on Thermo Gravimetric Analysis (TGA) of volatile-rich asteroidal regolith materials.

2.6. International Collaborations

- Bennett (with graduate student A. LeBlue-DeBartola) is continuing Collaboration with Univeristé de Lille, analyzing meteorites by generating hyperspectral Raman maps to determine organic-mineral associations as well as using Raman as a thermometer.
- Pinilla-Alonso worked on planning a robotic competition in Puerto Rico, hosted by the Arecibo Observatory. For those means, we started discussions on the goals and activities to be part of this competition, together with Francisco Cordova, director of the observatory. We will focus our efforts on the design of a lander and rover that would be able to perform specific tasks to clear small areas of the Moon's surface to build landing platforms.
- Britt is jointly advising a grad student at the University of Grenoble in ISRU related studies. Sebastien Cohoner will split his time between Grenoble and UCF in Orlando.
- Britt is working with Co-Is Chrysoula Avdellidou and Marco Delbo (Observatoire de la Côte d'Azur) on impact experiments using asteroid simulants, thermal cycling of regolith investigations, and physical properties investigations.
- Britt is partnering with Serkan Saydam of the University of New South Wales to assist on the integration of planetary science and ISRU into their very strong mining curriculum.
- Britt is working with Hideaki Miyamoto (University of Tokyo) on the development of simulants to support the JAXA MMX mission.

3. Public Engagement Report

3.1. Humberto Campins

- H. Campins engaged in a series of public talks, which included talks to a class of senior high school students, the Central Florida Astronomical Society, and an invited presentation at the American Association of Physics Teachers. He engaged in multiple press interviews with local and national reporters as well as at a DPS Press conferences relating to his work with the OSIRIS-REx mission, including reporting on the successful sampling of the asteroid surface.

3.2. Kevin Cannon

- Worked as an advisor with the Tinkering School (https://www.tinkeringschool.com) for their summer program offering students the ability to control robots remotely in an artificial Martian lava tube.

3.3. Mark Boslough

- M. Boslough was a panel member on the recurring webcast event, Asteroid Day. M. Boslough was also featured in the recent IMAX movie Asteroid Hunters that was released in October (Figure 19). He was a keynote speaker at the Coalition for Excellence in Science Education. Lastly, he is also a Near-Earth Object Rapid Response Team leader, which is responsible for getting subject matter experts to respond to new developments quickly.

Figure 19: CLASS Co-I M. Boslough was featured in the IMAX movie Asteroid Hunters.

3.4. Yanga Fernandez

- Y. Fernandez organized and ran an outreach program that made use of Robinson Observatory, UCF's campus observatory. We engaged the public in lunar and small-body science at many of these events. Due to the pandemic, some of our events were virtual – including our participation in the "International Observe the Moon Night" on September 26 and in the Jupiter-Saturn conjunction on December 21. About 150 people visited these events virtually.

3.5. Dan Scheeres

- D. Scheeres made a presentation to a group of Lockheed-Martin high school interns.

3.6. Kerri Donaldson Hanna

- K. Donaldson Hanna has been advising/mentoring a Lake Highland Preparatory High School Student, Aliza Hasan, on a research project on the irregular mare patches on the Moon. She participated in UCF's International Observe the Moon Night, giving a virtual talk entitled "Lunar Research at UCF" which can be viewed at https://youtu.be/yNJPjtNsFOQ.

3.7. Robert Jedicke

- R. Jedicke gave a lecture on asteroid mining to the Honolulu Science Café (live), as well as to the London Centre of the Royal Astronomical Society of Canada (via Zoom). He has given an interview with Popular Science. He was interviewed for an article on asteroid missions to appear in 'Engineering.' He was also interviewed for a documentary series on ssteroid mining. R. Jedicke was selected to be a California Academy of Science's Benjamin Dean Astronomy Lecturer, but this was canceled due to the pandemic.

3.8. Joel Sercel

- J. Sercel updated the TransAstra website (transastracorp.com) and YouTube channel with additional information about asteroid mining and ISRU.

3.9. Josh Colwell

- J. Colwell hosts the podcast "Walkabout the Galaxy" with CLASS deputy-P.I. Addie Dove and Jim Cooney. Frequent topics include exploration activities, including CLASS research and NASA exploration missions, and general science topics related to asteroids and the Moon. In 2020 there were over 84,000 downloads of 44 different episodes.
- Josh Colwell, Addie Dove, and Jim Cooney gave a presentation in the "Space Track" of the Dragon Con science fiction, fantasy, and space convention on September 5, 2020.

3.10. Kris Zacny

- K. Zacny has engaged in public outreach events with Auburn University, Michigan Tech, Colorado School of Mines, University of Puerto Rico, and University of California San Diego.

3.11. Paul Abell

- Girls and Technology presentation for Norway sponsored mentors visit "Chelyabinsk Impact Event and Planetary Defense" on October 24, 2019, in Houston, Texas.
- International Space Education Professional Development Program presentation "Chelyabinsk Impact Event and Planetary Defense" on February 5, 2020, in Houston, Texas.
- Space Exploration Educators Conference presentation "Asteroids and Space Exploration: The Hayabusa2 and OSIRIS-REx Missions" and hands-on activity for "Mission Asteroid!" educational game on February 8, 2020, in Houston, Texas.
- Fort Worth Geological Society Meeting presentation "The Age of Asteroid Exploration: The Hayabusa2 and OSIRIS-REx Sample Return Missions" on February 10, 2020, in Fort Worth, Texas.
- Texas A&M Galveston Geology 301 Guest Lecture (virtual) "Asteroids and Space Exploration: The Hayabusa2 and OSIRIS-REx Missions" on April 14, 2020, in Galveston, Texas.
- Guest lecturer for University of Maryland Dept. of Aerospace Engineering NEO Graduate Level Mission Design Course Fall 2020.

3.12. Cassandra Runyon

C. Runyon and D. Hurd participated in the following EPO events:

- National Park Service (https://www.nps.gov/subjects/nightskies/index.htm). Invited speakers to Dark Skies training for Rangers. March 2020, Death Valley (Event cancelled due to COVID-19).
- Abre Tus Sentidos A Los Eclipses: Sudamerica. Tactile Eclipse book in Spanish highlighting December 14, 2020 solar eclipse in Argentina and Chile. Book was distributed to Chilean and Argentinian Embassies in D.C. for distribution to respective countries. Partnered with Giant Magellan Telescope, GMTO Chile and Instituto de Tecnologías en Detecction y Astropartículas (ITeDA), CNEA-CONICET-UNSAM ITeDA Mendoza.
- Provided copies of all available tactile books to the United Nations Headquarters in Vienna for inclusion in a permanent display at the headquarters.
- Working closely with members of the Landsat 9 Team

to create and publish a tactile book on Earth and an introduction to climate change (see #1 above)

- Presented 30 virtual field trips on space science and exploration to over 600 middle school students using Stellarium planetarium program and tactile books.
- Worked with the National Institute of Health to develop and produce tactile book and associated activities highlighting light pollution.
- Panelist for the SciAccess Workshop, hosted by Ohio State University.
- Participant and presenter for NASA 508 Task Force hosted by NASA Marshall Space Flight Center.
- Invited Presentation/panelist – LPI Sharing Planetary Science: Engaging Audiences with Disabilities (11.04.20)
- Together with our SSERVI team we are planning a new series of workshops to share SSERVI science via accessible activities using Universal Design
  - o Caitlin Nolby and Marissa Saad – University of North Dakota Ph.D. students and North Dakota Space Grant leadership
  - o Jobi Cook, North Carolina Space Grant and North Carolina State University

3.13. Clive Neal

- C. Neal gave a public seminar at Notre Dame entitled “Why we should go back to the Moon”
- Cosmic Controversy Podcast: The Case for the Moon https://brucedorminey.podbean.com/e/episode-20-the-case-for-a-lunar-science-moon-rush/
- Blue Dot podcast: The case for Lunar Science https://www.mynspr.org/post/blue-dot-195-unraveling-mysteries-moon-planetary-geologist-clive-neal#stream/0
- ASCEND Infrastructure Workshop – panel member and co-convener. https://ascend2020.ascend.events/event/member/689647

4. Student/Early Career Participation

Undergraduate Students

1. Anna Metke, UCF, Exolith Lab manager.
2. Alex Perruci, UCF, Exolith chief engineer.
3. Jillian Gloria, UCF, Exolith Lab.
4. Christian Sipe, UCF, Exolith Lab.
5. Anna Paula Dova, UCF, Exolith Lab.
6. Janelisse Morales Gonzalez, UCF, Exolith Lab.
7. Makayla Peppin, UCF, Physical properties.
8. Parks Easter, UCF, Exolith Lab.
9. Joshua Conway, UCF, Exolith Lab.
10. Lucas Weber, UCF, Exolith Lab.
11. Jennifer, Nolau, UCF, OSIRIS-REx observations and interpretation.
12. Daniella, McCarty, UCF, OSIRIS-REx observations and interpretation.
13. Remington, Cantelas, UCF, OSIRIS-REx observations and interpretation and spectral observations of meteorites.
14. Zoë Bowers, Colorado School of Mines, undergrad working with K. Cannon.
15. Daniel Abel, Colorado School of Mines, undergrad working with K. Cannon.
16. Cheyenne Harper, UCF undergraduate student, sample preparation and testing temperature sensors.
17. Adam Bedel, UCF undergraduate student, testing thermal camera observations of lunar simulants.
18. Sarah Shores, UC San Diego, undergrad, research assistant working with R. Jedicke.
19. Shaw Newsom, UH, undergrad, research project with R. Jedicke.
20. Ben Workinger, Undergrad at Worcester Polytechnic Institute, TransAstra Intern COOP Student.
21. Conrad Jensen, Undergrad at Vanderbilt, TransAstra Intern.
22. Claudia Orozco Vega, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.
23. Gillian Gomer, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.
24. Jeb Massaro, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.
25. Melinda MacDonald, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.
26. Alexander Nicola, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.
27. Andrew O’Reilly, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.
28. Madison Weinberg, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J.

Figure 20: CLASS undergrads working in the Exolith Lab in the age of COVID.

Colwell.

29. Raquel Guzman, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.

30. Richard Wakefield, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.

31. Tyler Cox, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.

32. Yeniz Azconovieta, UCF, worked on CLASS-related projects at the Center for Microgravity Research under J. Colwell.

33. Alexander Wasilkoff, Boston College, development of computer algorithms to analyze raw thermo-physical meteorite data.

34. Adam Holland, Scotch college (high school), Adelaide, Australia. P Abell serves as an advisor to Mr. Holland for his major research project addressing future issues of space colonization with respect to resources and technologies.

35. Robert Lawrence, MTU, worked on designing, manufacturing the 20,000 lbs of MTU-LHT-1A lunar simulant for CLASS Co-I P. van Susante's sandbox and DTVAC use.

36. Sarah Swiersz, UCF, spectral measurements of pellets and powders (of simulant and meteorites), economic assessment of societal impacts of ISRU.

37. Riley Havel, UCF, spectral measurements of powders (CLASS simulants and meteorites).

Graduate Students

38. Anicia Arredondo, UCF, asteroid family observations and characterization.

39. Andrew Malfavon, UCF, asteroid observations.

40. Sarah Deitrick, Colorado School of Mines, grad, regolith simulants & GIS.

41. Hunter Danque, Colorado School of Mines, grad, GIS & machine learning.

42. Megan Harwell, UC Davis, Meteor Crater simulations.

43. Mary Hinkle, UCF, thermal modeling of asteroids.

44. Jennifer Larson, UCF, dynamical modeling of ejecta clouds from asteroids.

45. Vanessa Lowry, UCF, dynamical simulations of asteroid families, new work modelling thermal infrared spectra of asteroids and Trojan asteroids, training/working with Dr. Tim Glotch (RISE2) on T-matrix radiative transfer algorithms.

46. Ryan Galinkin, UCF, laboratory measurements of highly porous analog samples to constrain surface porosities of airless bodies.

47. Nick Piskurich, UCF, remote sensing analysis of the irregular mare patches on the Moon.

48. Autumn Shackelford, UCF, characterizing the effects of cold and 'wet' conditions on grain morphologies in regolith simulants.

49. Multiple graduate students funded at Colorado School of Mines for work on asteroid mining in TransAstra's Optical Mining Test Bed, funded partially by CLASS and partially by a TransAstra Phase 3 NIAC Contract.

50. Wesley Chambers, UCF, plume interactions. He has defended and has a permanent job at MSFC.

51. Stephanie Jarmak, UCF, mass-transfer events under microgravity (defended her PhD in May 2020).

52. Isabel Rivera, UCF, development of a numerical model to track ejecta from lunar rocket exhaust.

53. Craig Neal, UCF, working on thermogravimetric analyses of meteorites.

54. Katerina Slavicinksa, UCF, design and construction of a UHV space-weathering chamber and space weathering experiments.

55. Brian Ferrari, UCF, space-weathering experiments and helping construct UHV space weathering chamber.

56. Amy LeBleu-DeBartola, UCF, Raman investigations of carbonaceous chondrites.

Postdoctoral Fellows

57. Jaun, Luis Rizos, UCF, asteroid family observations and characterization.

58. Mélissa Martinot, UCF postdoc, remote sensing analysis of pure anorthosite regions on the Moon and laboratory measurements of lunar analogs.

59. Tamil Selvan, UCF, research associate working with S. Seal. on x-ray diffraction studies.

60. Jared Long-Fox, UCF, Geotechnical Analysis.

61. Zoe Landsman, UCF, now Exolith Lab Chief Scientist.

62. Leos Pohl, UCF, Asteroid physical properties.

6. Mission Involvement

Figure 21: PlanetVac regolith Sampling system being tested on a Masten Space Systems lander in Mojave, California.

1. Lucy, D. Britt, Leader of the Interior and Bulk Properties Working Group, Co-Investigator.

2. New Horizons, D. Britt, Co-Investigator.

3. OSIRIS-REx, H. Campins, Mission Science Team, with SSERVI funding to help involve and support undergraduate and graduate students allowing them to get first-hand experience analyzing mission data.

4. OSIRIS-REx, R. Macke, Collaborator, SSERVI has helped facilitate R. Macke's involvement in the mission, and upcoming role measuring physical properties of Bennu return samples.

5. OSIRIS-REx, D. Scheeres, Co-Investigator, Participating in post-TAG analysis of surface interactions.

6. OSIRIS-REx, K. Donaldson Hanna, Participating Scientist.

7. OSIRIS-REx, C. Opeil, In collaboration with Andrew Ryan, will be taking heat-capacity measurements on returning samples of Bennu returned by OSIRIS-REx. Work with CLASS helped pave the way to demonstrate that we can perform these measurements with high fidelity.

8. OSIRIS-REx, P. Abell, Acting NASA Representative, facilitating coordination of proximity activities for science and exploration objectives between Hayabusa2 and the OSIRIS-REx teams.

9. Lucy, R. Macke, Science Team, Interior and Bulk Properties.

10. DART, M. Boslough, is planning to scale up simulations to the DART impact target and use fragment tracking as an independent means of estimating β, the momentum enhancement factor.

11. DART, D. Scheeres, Co-Investigator, participating in modeling of rubble-pile secondary after impactor impulse and working on detailed dynamical models of the Didymos system to help enable interpretation of mission observations.

12. DART, P. Abell, ground-based observations, impact, modeling, ejecta, and proximity science working groups.

13. NEOWISE, Y. Fernandez, Collaborator, comet group.

14. NEO Surveyor Mission (NEOSM), Y. Fernandez, Co-Investigator. This mission concept (PI: Amy Mainzer) is in extended-phase A and will move to phase B in 2021.

15. NEOSM, P. Abell, participating as a science team member for identification of small body targets with low delta-V's, which is of interest for NASA's resource utilization and exploration objectives. Also participating on the comet working group to help model the numbers of comets that may be identified by NEOSM and the proportion of these objects that represent and impact hazard to the Earth.

16. Mission Concept Study "In Situ Geochronology for the Next Decade: Mission Designs for the Moon, Mars, and Vesta" led by CLASS Co-I B. Cohen studies mission concepts to these targets and incorporated significant contributions from CLASS space industry partners (e.g., Kris Zacny).

17. Janus, D. Scheeres, Principal Investigator, this is a NASA SIMPLEx mission to flyby two binary NEAs, now in phase C and will share a launch with Psyche in Aug/Sept 2022.

18. Janus, R. Jedicke, Co-Investigator.

19. Lunar Reconnaissance Orbiter, K. Donaldson Hanna, Diviner Lunar Radiometer, Co-Investigator.

20. Lunar Compact InfraRed Imaging System (L-CIRiS), K. Donaldson Hanna, Co-Investigator.

21. Lunar Trailblazer, K. Donaldson Hanna, Co-Investigator.

22. ESA Comet Interceptor, K. Donaldson Hanna, MIRMIS, Instrument Team Member.

23. MiniBee Asteroid Mining Technology Demonstrator, J. Sercel, Principal Investigator.

24. Q-PACE Cubesat, J. Colwell, Principal Investigator, NASA SIMPLEX mission; CLASS has helped perform experiments and funding for projects directly in support of this mission.

25. Q-PACE CubeSat, A. Dove, Co-I.

26. Martian Moons eXploration (MMX), K. Zacny, Project Manager for Pneumatic sampler.

27. VIPER (rover) and PRIME1 (lander), TRIDENT drill, K. Zacny, Principal Investigator.

28. Hyabusa2, P. Abell, participating as a team member on the Multi-Scale Science Working group, the International Regolith Science Working Group, and the On-board Navigation Camera (ONC); facilitates interactions among Japanese and US team members as agency liaison to JAXA on behalf of NASA.

29. Hera Mission, P. Abell, participating as a US member and mission advisor on the Hera mission investigation team to aid the characterization of the Didymos post-DART impact. Also participating as an advisor to the European Commission Near-Earth Object Modeling and Payloads for Protection (NEO-MAPP) project.

30. MMX Mission, P. Abell, Advising JAXA personnel on how the Martian Moons eXploration (MMX) mission has ties to Human SKGs and aid in the participation of NASA interests from both SMD and HEOMD perspectives.

31. MMX Mission, R. Mueller, Technical advisor, R. Mueller at NASA Kennedy Space Center & SSERVI CLASS member is the technical advisor for the Pneumatic Sampler being provided by NASA to JAXA. Valuable scientific information was provided by Dr. Dan Britt (SEERVI CLASS) to inform sampling strategies and the sampler design. The JAXA MMX mission is proceeding to the Preliminary Design Review (PDR) milestone and has full funding for the Pneumatic sampler which is due to fly on the JAXA MMX spacecraft in 2024.

32. Lunar CLPS Mission 2023, R. Mueller, NASA KSC Swamp Works is collaborating with CLASS space industry partner Honeybee Robotics, inc. to test an engineering model of the PlanetVac sampling system in a regolith simulant test bed at KSC. The sampler is planned to fly on a Commercial Lunar Payload Service (CLPS) lander in about 2023.

33. Landsat 9, C. Runyon (and D. Hurd), Continue to work with EPE contacts regarding Landsat 9 launch (September 2021) and Earth tactile book. Our role is to highlight Landsat 9 mission directives and instruments through a tactile book for blind and visually impaired students.

34. Lunar Geophysical Network Planetary Mission Concept Study, C. Neal, Co-I.

35. CLPS 2021 and 2022 Missions, P. van Susante, collaborating with SpaceBit.

7. Awards

Humberto Campins: Received two awards from the Florida Space Grant Consortium.

Christopher Bennett received three awards from the Florida Space Grant Consortium.

Joel Sercel was awarded his 6th NIAC fellowship in June 2020 for his phase 2 NIAC on the Lunar Polar Mining Outpost which includes his work on the Lunar Sun-Flower Power Tower and Radiant Glass Dynamic Mining.

Sarah Swiersz (UCF undergraduate student, working under CLASS deputy-P.I. Bennett) and Stefanie Jarmak (UCF graduate student working under CLASS Co-I Josh Colwell) were both named to the order of Pegasus, the highest honor bestowed upon students by UCF.

Katerina Slavicinska (UCF graduate student, working under CLASS deputy-P.I. Bennett) was selected to receive a FINESST award to study the effects of carbon and organics on space weathering processes occurring within carbonaceous meteorites.

Rob Mueller received a NASA Team Silver Achievement Medal (shown to the left) for supporting the NASA Centennial Challenge Competition: “3D Printing a Mars Habitat,” as a co-founder, judge, and rules committee member. This prestigious NASA Silver Achievement Medal is awarded to Government and non-Government individuals or teams by NASA Center Directors for a stellar achievement that supports one or more of NASA’s Core Values, when it is deemed to be extraordinarily important and appropriate to recognize such achievement in a timely and personalized manner.

Center for Lunar Science and Exploration (CLSE)

David Kring

Lunar and Planetary Institute, Houston, TX

CAN-3 TEAM

1. CLSE Team Report

The team conducted lunar science, contributed to robotic and human exploration planning, developed and managed training activities, and provided community services.

1.1 Science and Exploration

> Importantly, while CLSE conducts basic science research, a large fraction of the team's science is designed to address agency exploration issues. For that reason, our report combines the results of science and exploration activities.

1.1.1 Distribution of Lunar Volatiles

CLSE continued to study the thermal stability of volatiles in the south polar region and the resource potential constrained by that parameter. Because near-surface ice deposits that do not require energy for the removal of overburden may be attractive ISRU targets, our initial focus was on the resource potential of ices within the uppermost meter of regolith.

CLSE integrated an assessment of volatile sources with the production and modification of polar catchments for volatiles as the surface of the Moon was affected by impact cratering processes. To illustrate the consequences of evolutionary processes affecting the Moon, we devised a notional stratigraphy of volatile deposits in three polar craters (Fig. 1). Because those craters formed at different times, the volatiles delivered to them will have been different. We also point out that polar volatiles cannot be discussed only in terms of sources and deposition, because other processes, among them ballistic sedimentation, can modify those deposits. To illustrate that point, we calculated the ballistic speeds of impact ejecta hitting the floors of those same three impact craters (e.g., as in Fig. 2 for Shoemaker crater). Impact ejecta from younger cratering events hit the floors of those craters with speeds of order 1000 km/hr, which should have eroded and mixed underlying material. When the impact debris landed at such high speeds, did it vaporize any volatiles in the regolith? If so, did the volatiles escape and get trapped elsewhere in the polar region? Or were the volatiles incorporated into the mixed ejecta blanket? Those are questions to be addressed next.

In a review of lunar resources, CLSE found that impact cratering is the most important physical process affecting lunar ISRU: (a) The topography of impact craters in the

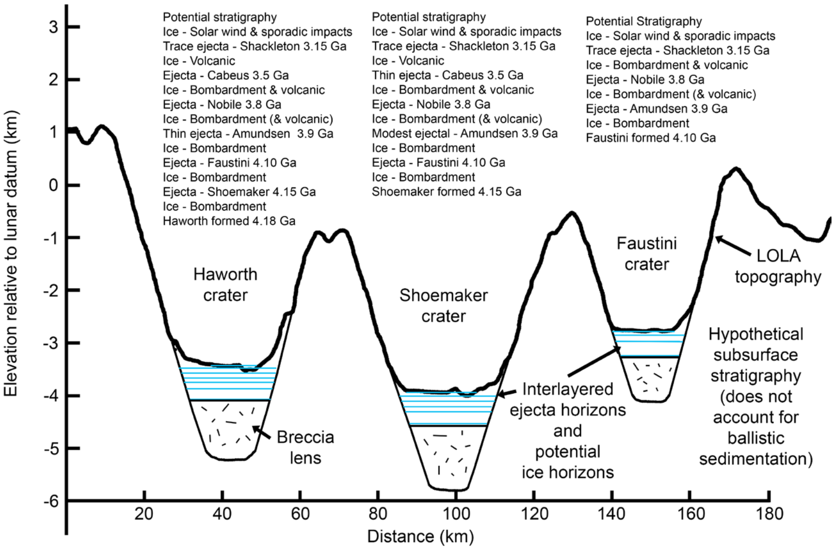


Figure 1. Notional stratigraphy of ice deposition and impact ejecta on the floors of three south polar craters: Haworth, Shoemaker, and Faustini. The topography is derived from LOLA data. A breccia lens is assumed to underly the original surface of the crater floor, based on observations of terrestrial craters.

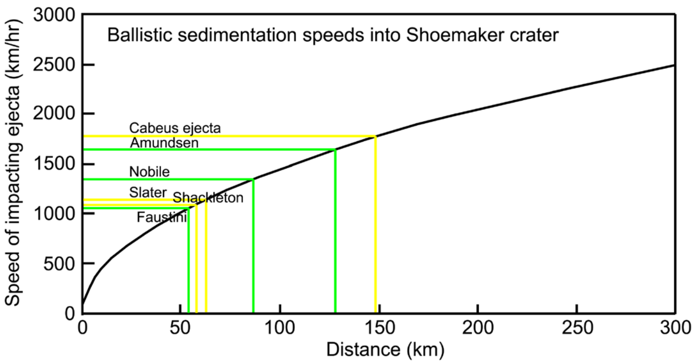


Figure 2. Speeds of ballistically emplaced ejecta into Shoemaker crater from nearby craters (Scott, Amundsen, Nobile, Cabeus, Slater, and Shackleton). If Shoemaker is within a crater diameter of a source crater, a continuous ejecta blanket is likely and indicated with a green line. If Shoemaker is within two crater diameters of a source crater, then it is indicated with a yellow line. Speeds are scaled in kilometres per hour. For those who prefer to think in kilometres per second, 0.1 km/s is 360 km/hr and 1 km/s is 3600 km/hr. The escape velocity of the Moon is ~2.4 km/s.

polar regions produces the permanently shadowed regions (PSRs) where volatiles can be trapped; (b) Impacting asteroids and comets were a source of volatiles that could be trapped in those PSRs; (c) The largest impact events altered the spin of the axis of the Moon and, thus, the locations of PSRs where volatiles could accumulate; (d) The largest impact basins thinned the crust, allowing large volumes of magma to reach the surface and vent volatiles, providing another source of volatiles that can be trapped in PSRs; (e) Impact ejecta from cratering events covered and potentially reworked via ballistic sedimentation horizons of ice deposited in PSRs, producing a stratigraphic succession (Fig. 1); (f) Ancient impact basins provided catchments for flood basalts (mare) that contain ilmentite that can be chemically modified to produce oxygen; (g) Ongoing impacts, including micrometeoritic impacts, have infused the regolith with meteoritically-derived volatile elements and those volatiles, when combined with volatiles from the solar wind, provide a recoverable reservoir everywhere on the Moon; (h) They have also infused the soil with meteoritic metal, which is another potential resource for a sustainable exploration program; and (i) The largest of the impacts produced melt sheets that may have differentiated, potentially forming ore deposits of metal and sulfide.

1.1.2 Rover Access of PSRs and Other Exploration Sites

CLSE's Exploration Science graduate student interns developed a method for assessing regolith bearing capacity that might affect trafficability of rovers in PSRs and the south polar region. A result we reported last year was published this year: There was no detectable degradation of bearing capacity as one passed from a sunlit region into the outer margins of a PSR (Sargeant et al., 2020). The data do not allow us to constrain trafficability within colder portions of PSRs, but the data do suggest that trafficability may not be as poor or deteriorate as quickly as some investigators in the community feared. This year we applied that same method for assessing regolith bearing capacity to the south polar region where VIPER and Artemis assets are to be deployed (Bickel and Kring, 2020). In the immediate vicinity of the south pole, estimated bearing capacities are similar to the values derived from equatorial highland regions of the Moon that were successfully traversed in the past. Those values were derived from measurements of boulder tracks and a quantitative relation between track depth, local slope angle, and circumpolar bearing capacity. This relation was used to map the approximate surface strength of the sunlit lunar south polar region as a function of topography (Fig. 3). The resulting product was applied to study the estimate sinkage of exploration rovers on slopes, indicating that sinkage-related issues might only start to occur on inclines steeper than 25°, while the potential for local, slope independent, mechanical strength anomalies remains. The results of the study show no evidence that future south polar surface operations would be affected by insufficient sunlit regolith bearing capacities.

The student on that project extended that study of polar boulders and boulder tracks to a global assessment of

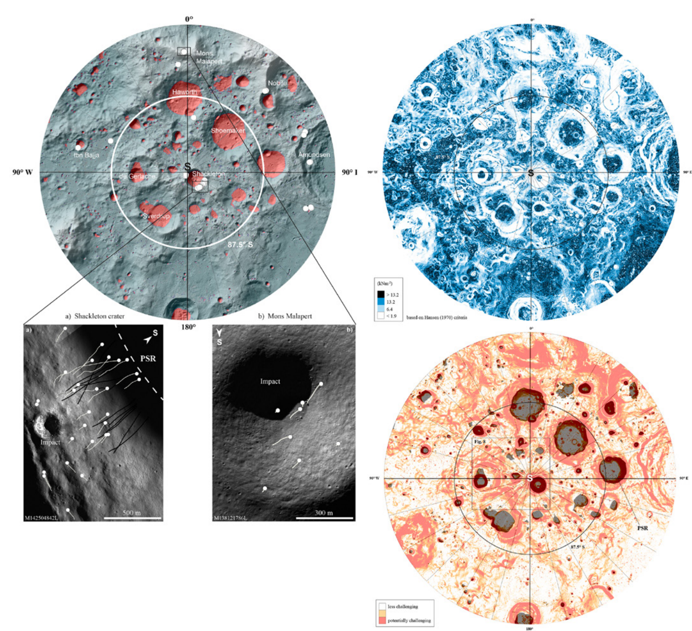


Figure 3. Study region (top left), examples of boulder tracks used to assess regolith bearing capacity (bottom left), estimated bearing capacities (top right), and map of areas (orange and red) where additional rover sinkage is possible (bottom right).

rockfalls on the Moon as part of his thesis studies in Europe. He generated a new global map of over 136,000 rockfalls generated over billions of years on the Moon (Bickel et al., 2020).

1.1.3 Geology of Artemis Exploration Zone and EVA Options

In addition to a trafficability assessment of the south polar region, we examined the geology of Shackleton crater and potential EVA targets for Artemis crews (Gawronska et al., 2020). The study revealed Shackleton crater excavated material from two types of target terrains (Fig. 4): a crystalline terrain composed, in part, of purest anorthosite and potentially a product of the lunar magma ocean; and a layered terrain that appears to be a sequence of impact ejecta blankets from nearby polar craters (e.g., Amundsen, de Gerlache, Nobile, Slater, Sverdrup, and Cabeus). The layered sequence covered crystalline terrain on one side of the massif excavated by the Shackleton impact event. EVA sample sites include Shackleton ejecta and small PSRs.

In parallel, we used a computer hydrocode to examine the impact event that produced Shackleton crater (Halim et al., 2020). The impact simulation resolves the size of the asteroid responsible for the crater (Fig. 5), the thickness of ejecta on the rim of the crater, and demonstrates that volatiles in the target can affect the final morphology of the crater. Indeed, if volatiles lurked in the layered terrain seen in our geologic study (Gawronska et al., 2020), then they may be responsible for a slight asymmetry observed in Shackleton rim morphology.

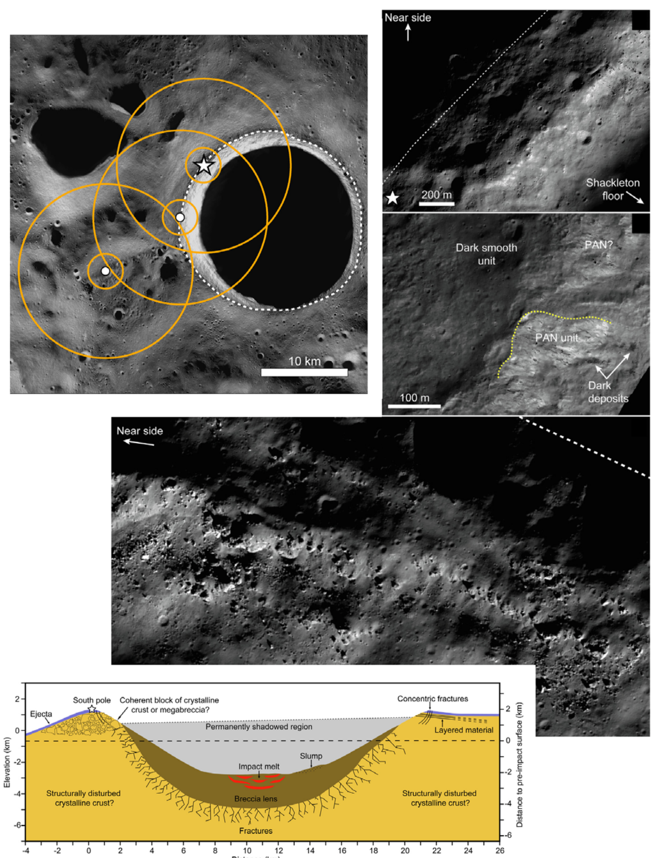


Figure 4. Geologic studies of three potential landing sites near the rim of Shackleton crater (top left) reveal that Shackleton crater excavated lunar anorthosite (seen in crater walls in two upper right panels) and a layered terrain (seen in crater wall in lower right panel), which are used to generate a geologic cross-section of Shackleton crater (bottom panel).

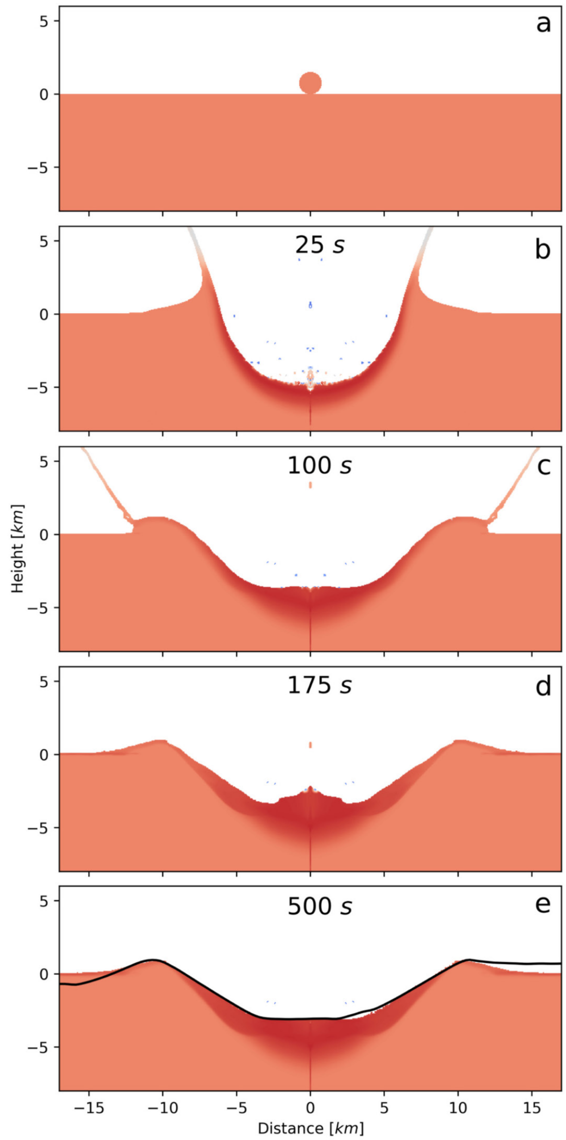


Figure 5. The observed morphology of Shackleton crater can be produced by a 1.5 km diameter asteroid with a chondrite-like composition vertically impacting a gabbroic anorthositic target at 15 km/s. If the impact had a shallower 45° trajectory, the asteroid may have had a diameter of 1.75 km and velocity of 15 km/s or a diameter of 1.5 km and a velocity of 20 km/s. Impact melt is generated during the impact, with most of the melt volume ponding on the crater floor. We introduced a water-bearing layer at various depths in the target and find that the burial depth of a volatile layer influence the final crater morphology and may explain the morphology of Shackleton crater.

Responding to a request from NASA, we augmented those results with additional studies to provide landing site and EVA options for the Artemis III mission and subsequent Artemis missions to the lunar surface. Collectively, CLSE delivered to the agency study results for more than a half-dozen sites within 6° of the lunar south pole (Fig. 6), which is the region identified in NASA's Artemis Plan for the Artemis III landing site and Artemis base camp. Other CLSE contributions included outlines for instrumentation to be deployed by crews to address science and ISRU exploration goals. Several of CLSE's civil servants (Sam Lawrence, Jeremy Boyce, and John Gruener) served on the Artemis III Science Definition Team and CLSE team member Amy Fagan served as a community consultant.

CLSE also responded to several agency requests for input to Lunar Surface Science operations. We described how the heterogeneous distribution of water and dry ice may affect ISRU potential; how subsurface surveys with a crewed rover can be used to address both scientific and ISRU objectives; how small pressurized rovers can enhance lunar surface science productivity; and how a coordinated robotic exploration program can smartly test orbital detections of water and those detections' implications for resource potential.

1.1.4 Sources and Compositions of Lunar Volatiles

Determining the sources of volatiles is an objective of lunar exploration (NRC, 2007), in part because they provide a constraint on the evolution of volatiles in the Solar System. Sources also affect the chemistry of any polar ice deposits, which, in turn, affects any ISRU protocol for recovery. One source of volatile substances is meteoritic material. In model calculations of polar volatiles, the composition of that material is estimated based on the composition of past and present-day meteorite falls on Earth. For the first time, we directly measured the isotopic composition of volatiles in a bona fide remnant of an asteroid that hit the Moon: the Bench Crater meteorite found in an Apollo 12 soil. The Bench crater meteorite is characterized (Joy et al., 2020) by δD values between -36 ± 40 and 200 ± 40 ‰, and bulk average δ13C of -13 ± 30 ‰, and δ15N of -40 ± 360 ‰ (all uncertainties at the 2σ confidence level), which is an unusual combination of values. That said, it is also true that the oxygen isotope compositions measured in-situ in matrix silicates and magnetite in the Bench Crater meteorite are consistent with those measured in matrix and magnetite in CI and CM chondrite falls on Earth. Collectively, the new H, C, N, and O isotope data, coupled with mineralogical and geochemical observations, suggest that the Bench Crater meteorite in the lunar regolith may be derived from an asteroidal parent body not represented in terrestrial meteorite collections.

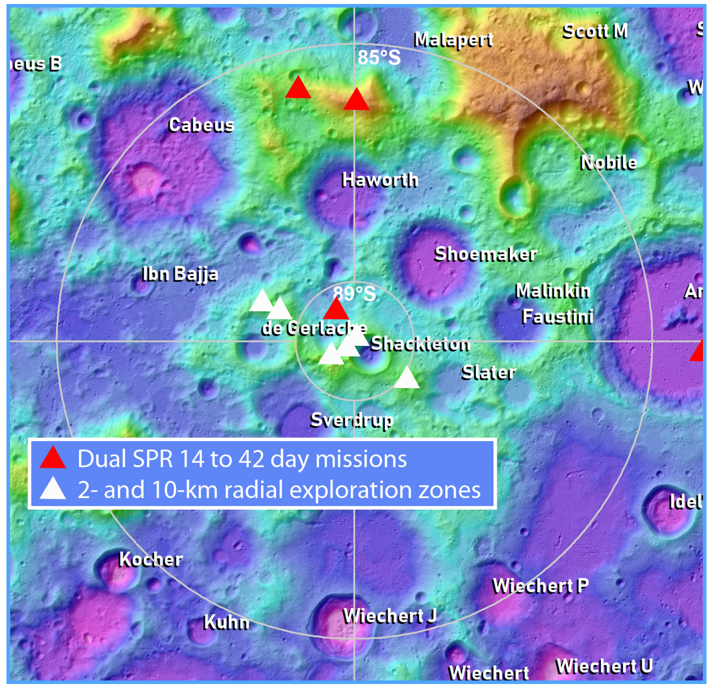


Figure 6. Locations within 6° of the lunar south pole, the initial Artemis exploration zone, that the CLSE team has studied for different types of human mission scenarios, including 2-km-diameter walking EVAs, 10-km-diameter unpressurized rover EVAs, and greater distance traverses using dual small pressurized rovers.

While a portion of our team was examining exogenous sources of volatiles, some of our international partners (Stephant et al., 2020) were examining hydrogen isotopic compositions of lunar melt inclusions and deduced that both magmatic and secondary processes affected those compositions.

1.1.5 Collisional Evolution of the Lunar Surface

Another group of international partners (Nemchin et al. 2020) re-examined the geochronology of the Imbrium impact event, the basin visited by Apollo 15 astronauts and the source of debris found at several other Apollo landing sites. Using the U-Pb method, they determined the age of Imbrium is 3922 ± 12 Ma. They then reviewed 40Ar/39Ar step-heating ages available for impact melt samples from different landing sites and found that the majority provide robust plateau ages that are indistinguishable within uncertainties and generate a weighted average age of 3916 ± 7 Ma and a median average age of 3919 ± 14 Ma, both of which agree with U-Pb result.

1.2 Training

CLSE developed and maintained training programs for students and professionals engaged in lunar surface exploration.

1.2.1 Space Flight Resource Management Training for Science Operations

To begin training scientists to work in a flight operations environment during lunar surface EVA, we developed a two-week, immersive training activity using facilities at the Johnson Space Center's (JSC's) flight training facility, with additional instructional content presented at the Lunar and Planetary Institute (LPI). Participants will be taught space flight resource management (SFRM) skills, learn to develop and share situational awareness in a complex mission environment, learn to develop better active listening skills, learn communication protocols, how to package comm-loop calls, and problem solving skills relevant to a human mission environment. In addition, participants will discuss Gateway-related operations, including a required tele-operation element, the evolving Design Reference Mission (DRM) for lunar surface landing sites and traverses, and an introduction to EVA ops using the new Exploration Extravehicular Mobility Unit (xEMU) for astronauts. Those activities will be integrated with two lunar mission simulations that the Flight Operations Directorate (FOD) developed for training purposes. Instruction will be provided by CLSE P.I. Kring and staff from JSC's FOD and EVA training teams. We accepted applications for the first edition of this training course (scheduled for August 3-14, 2020), but had to postpone that activity because of the health emergency.

1.3 Exploration Science Summer Intern Program

Due to the pandemic-related restrictions, we had to modify our Exploration Science Summer Intern Program. Selected students were unable to travel to our training and research facilities in Houston. Moreover, facilities at both LPI and JSC were closed. Thus, we created and completed a special "virtual" edition of the program. Despite being separated by more than a thousand miles, the team of students produced wonderful geologic insights about two potential landing sites in the lunar south polar region. Those results were used in contributions to the Artemis III Science Definition Team and will be presented at the next Lunar and Planetary Science Conference.

1.4 Community Service

In addition to providing products for the agency, the CLSE team tries to support the broader lunar community with several services. Among them are the Lunar Science and Exploration information portal and the Lunar South Pole Atlas.

1.4.1 Lunar Science and Exploration Portal

The lunar community has grown dramatically with the development of new lunar programs. By one measure, the community has doubled in size in the last 18 months.

Figure 7. Electronic address for the Lunar Science and Exploration information portal.

New members of the community have been seeking resources, so we recently re-introduced our Lunar Science and Exploration portal (Fig. 7) through a series of community-wide email announcements. Each of seven emails described the content of the portal, which is immense and continues to grow. Several new documents were added during the health emergency, including a new series of illustrations about lunar water abundances. Sectional titles are (i) Apollo-era Documents, (ii) Lunar Maps and Atlases, including LPI's Lunar South Pole Atlas; (iii) Lunar Samples; (iv) Lunar Surface; (v) Lunar Landing Site Studies; (vi) Lunar Mission Timeline; (vii) Lunar Exploration Strategy Documents; (viii) Exploration Hardware; (ix) Computational Tools; and (x) Lunar Education.

1.4.2 Lunar South Pole Atlas

CLSE continued to contribute products to the LPI Lunar South Pole Atlas. This year's contributions included a new slope map, shaded relief geological map (Fig. 8), and several illustrations.

2. Inter-team/International Collaborations

2.1 Science and Exploration Research

CLSE continued to collaborate with a University of Colorado SSERVI team in studies of lunar surface missions on the farside that can address both geologic and astrophysical objectives.

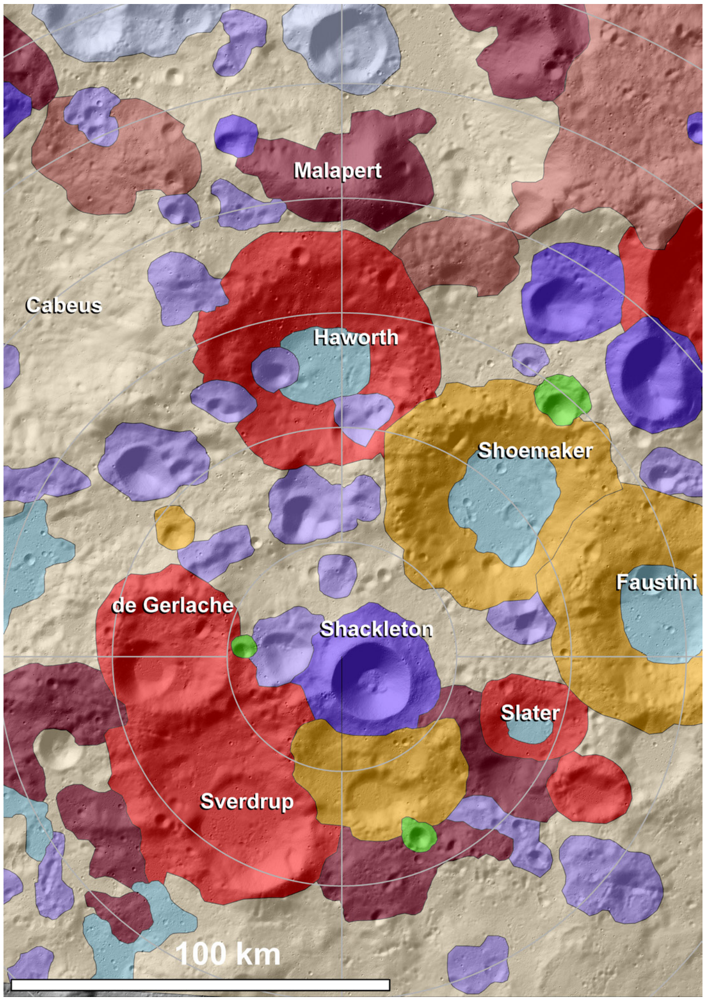


Figure 8. Detail from a shaded relief geological map of the south polar region of the Moon. The full-size map, with legend, is available in the LPI Lunar South Pole Atlas (https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/).

CLSE worked with a JSC ISRU group to develop a series of experimental studies that can bridge activities between CLSE and the Ames Research Center SSERVI team.

CLSE studies of lunar volatiles were greatly enhanced by contributions from international partners in the United Kingdom.

CLSE studies of lunar polar geology and lunar farside geology were greatly enhanced by work done by international partners in Germany.

2.2 Training and Education

CLSE supported a lunar and asteroidal ISRU class organized by the University of Central Florida SSERVI team.

Pandemic restrictions reduced our Exploration Science summer intern program to students residing in the United States, but previous exploration science interns, in several partner countries, contributed to this year's studies of lunar south pole geology (e.g., Gawronska et al., 2020; Halim et al., 2020).

3. Public Engagement

CLSE continues participation in two long-standing, successful education and public engagement programs: Exploration of the Moon and Asteroids by Secondary Students (ExMASS) and International Observe the Moon Night.

3.1 Exploration of the Moon and Asteroids by Secondary Students (ExMASS)

The Exploration of the Moon and Asteroids by Secondary Students (ExMASS) program engages high school students in authentic, student-led, lunar/asteroid research projects. Selected teams are paired with a professional scientist to guide them through the research process.

3.1.1 2020 ExMASS Program Overview

Ten schools were selected in spring 2020 to participate in the 2020-2021 ExMASS program (Figure 9). Approximately 50 students began the program in August 2020. Because the ExMASS program is virtual by design, the ongoing pandemic has not had a significantly negative effect on the program. Student teams will present their research in the spring of 2021, competing for a chance to present for the 2021 Exploration Science Forum.

3.1.2 Science Education Research Studies

In 2020, CLSE began collaborating with science education researchers at the University of Houston-Clear Lake to examine the impact of the ExMASS program on students, teachers, and advisors. Researchers will identify characteristics of the scientist-student team relationship and the impact of this relationship on the success of students in the program. They will also attempt to contact

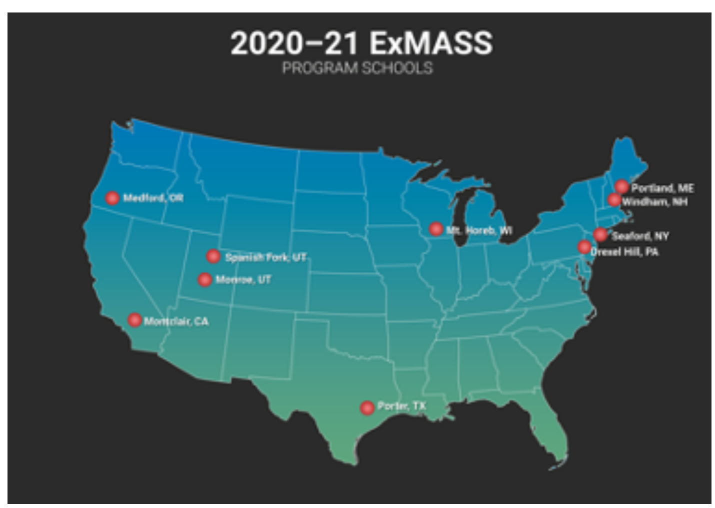


Figure 9. Locations of 2020-2021 ExMASS schools. Credit: LPI.

past student participants to determine the program's impact on their career choice. In addition, data will continue to be analyzed to evaluate the program's impact on participants attitudes toward science and science careers (Shaner et al., 2018).

3.2 International Observe the Moon Night

CLSE engagement lead Shaner continues to serve on the International Observe the Moon Night coordinating committee. His responsibilities include recruiting potential U.S.-based collaborators and assisting with the translation of various event documents into multiple languages. The 2020 International Observe the Moon Night was a virtual event. The LPI, NASA Goddard (LRO), NASA Ames (SSERVI), and the Planetary Science Institute produced a six-hour event featuring these institutions and was broadcast live on NASA TV and streamed through NASA's various social media platforms. Shaner was a Co-lead in the planning of the event and served as a host during the event.

4. Student/Early Career Participation

Due to the pandemic, CLSE had to make adjustments to its Exploration Science summer intern program. A virtual edition of the program was designed to give the students a positive experience while generating output to assist the exploration of the lunar south pole. Four of the originally selected students, from Los Angeles to New York, were able to participate in the virtual program. Due to the pandemic, field-based student activities were canceled.

Graduate Students

1. Jordan Bretzfelder (University of California, Los Angeles)
2. Indujaa Ganesh (University of Arizona)
3. Nandita Kumari (Stony Brook University)
4. Antonio Lang (State University of New York, University at Buffalo)

Postdoctoral Fellows

1. Dr. Katharine Robinson (USRA-LPI)

Promoted and/or New Responsibilities

1. CLSE Deputy Team Leader Debra Needham was promoted to a position at NASA Headquarters as a Program Scientist in the Exploration Science Strategy and Integration Office (ESSIO).
2. Science team member Amy Fagan was granted tenure at Western Carolina University.
3. Exploration Science intern Hannah Sargeant was awarded a doctorate for her thesis "Making Water from the Lunar Regolith."

5. Mission Involvement

CLSE is assisting the agency with studies that support the Artemis program (section 1.1 above) and its CLPS robotic lander program, including the 2024 CLPS mission to the Schrödinger basin.

6. Awards

At the NASA Exploration Science Forum, CLSE team members Amy Fagan and Harry Hiesinger were recognized for their special accomplishments. Prof. Hiesinger received the Angioletta Coradini Mid-Career Award and Prof. Fagan received the Susan Mahen Niebur Early Career Award.

Exploration Science Pathfinder Research for Enhancing SS Observations (ESPRESSO)

Alex Parker
Southwest Research Institute, Boulder, CO

CAN-2 TEAM

1. ESPRESSO Team Report

COVID-19 presented severe challenges to numerous planned Project ESPRESSO activities in 2020. First among our concerns is always maintaining team safety and the safety of the communities we live and work in. Access to laboratories and other facilities was heavily curtailed, hiring challenges prevented filling postdoc vacancies that opened as team members moved on to permanent positions, all group fieldwork was suspended, and the cessation of international travel resulted in cancellation of all of our team's reduced gravity flights at Canada's NRC-CNRC Flight Research Laboratory. Laboratory capabilities were distributed among team members' homes where possible, enabling instrument development and granular mechanics experiments to continue, albeit at a reduced pace. In the following sections, we highlight the areas and efforts that have made the most progress under these conditions in 2020, and we identify where further plans were stymied by COVID-19 related challenges.

1.1. Remote Active Spectroscopy with a Tunable Spatial Heterodyne Spectrometer

In 2019, Project ESPRESSO team members implemented a new spatial heterodyne spectrometer design optimized for Raman and LIBS applications where extremely high throughput and high spectral resolution is required in parallel with a broad range of accessible wavelengths from a single instrument. The spectrometer is tunable with only one mechanical degree of freedom; optical components rotate around a common axis on a single rotation stage, enabling a deterministic central wavelength sweep with no subsequent calibration or alignment required. In spite of the interferometric nature of the instrument, the robustness of the new optical design permits the majority of the metering structure to be constructed from 3D printed plastic. In 2020, the performance of this spectrometer was further improved and tested by collecting standoff Raman and fluorescence spectra of a number of compounds, including sulfur, ruby, and graphene. With each of these compounds, the spectral bandpass was swept over a region around the excitation line to confirm that the instrument performance remained consistent without requiring additional tuning after moving the bandpass center.

The benefits of this instrument to exploratory science are substantial – any individual Raman lines can be profiled in extreme detail from a single instrument; for example, if quartz grains are identified in a sample, the shape of the Raman lines of that quartz can be used to constrain the maximum shock ever experienced by the sample. If a different compound is identified in another sample with completely distinct Raman lines, the instrument can easily accommodate detailed profiling of those lines instead. This rapid tuneability renders it an optical Swiss Army knife for mineralogical analysis within a single robust instrument.

1.1.1. COVID Impacts on Remote Spectroscopy Efforts

Integration of our spatial heterodyne spectrometer and other active spectroscopy instrumentation into the Boulder Laser Ablation of Standoff Targets for Exploration Research Laboratory (BLASTERLab) high vacuum chamber facility has been suspended due to limited laboratory access during COVID-19. This high vacuum chamber was integrated into the laboratory to enable access to lunar-like pressure environments to accurately capture the plasma dynamics of a Laser-Induced Breakdown Spectroscopy (LIBS) ablation pulse when targeting lunar analog materials. The goals of BLASTERLab efforts are to understand the performance of a variety of LIBS configurations in the lunar and asteroid environment to better enable future long-range active spectroscopic instruments on the Moon and asteroids. These efforts remain on hold until multiple personnel required for safe operation of the facility can access the laboratory simultaneously.

1.1.2. Reduced-Gravity Impact and Granular Mechanics Experiments

Planned 2020 efforts included experiments conducted in lunar gravity and asteroid-like gravity on board reduced-gravity flights from the NRC-CNRC Flight Research Laboratory. All of these experiments have been put on hold until such time as international travel is safe for all parties.

In January-March 2020, team members procured and assembled components for a set of six chambers to conduct dam-break experiments onboard the planned reduced gravity flights. These chambers would operate under lunar gravity and carry samples of lunar regolith simulant to provide experimental validation of lunar landslide models used for operational safety planning.

In March 2020, team members designed, assembled, and tested a launcher for the 3rd generation instrumented impactor that would enable it to be fired into a regolith bed under vacuum in reduced gravity. This was to be included in the payload of our 2020 reduced gravity flights to extend the instrumented impactor dataset to cover lunar and microgravity regimes.

In January-March 2020, team members collaborated with members of the GEODES team to develop and implement an experimental rig to validate their models of the brazil nut effect in reduced gravity. A simulated clast was to be tracked through a column of simulated regolith using an embedded magnet and an array of Hall effect sensors. During periods of reduced gravity onboard our flights, a set of controlled shakes would be applied to the column and recorded with an IMU. The motion of the embedded clast through these shakes and integrated over the nearly 5 minutes of lunar gravity available during a single flight would be compared against predictions by the GEODES team.

1.2. Scaling Up Reduced-Gravity Vacuum Chambers for Lunar and Asteroid Environmental Testing

After our successful 2018 reduced gravity flight campaign, the Project ESPRESSO team sought to scale up the flight vacuum chambers to enable larger-scale environmental testing on lunar- and asteroid-like surfaces, at relevant gravity and pressure levels. We developed set of six 60-liter environment chambers that can be flown simultaneously, each containing independent experiments. Before COVID-19 related lab closures, we had implemented multiple port and experiment configurations, including the chamber shown on the right with a large external extension housing a projectile launcher for impact experiments into lunar regolith at relevant g-levels. These chambers are low cost and lightweight, and can be easily shipped to other teams seeking to integrate experiments in advance of future flight campaigns.

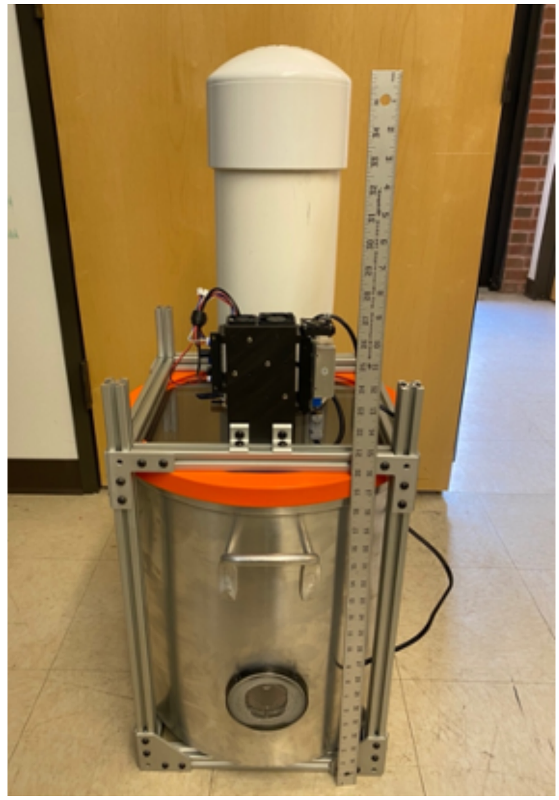


Figure 1: One of six new 60-liter reduced gravity vacuum chambers, shown configured with external projectile launcher (white).

Further, we are investing in a larger series of 250-liter cubic chambers. We anticipate flying up to three chambers simultaneously to permit relatively large flight hardware to be tested under interaction with lunar regolith at lunar gravity and pressure levels. These chambers will be available for 2021 flight campaigns, or as soon as post-COVID flights may resume.

1.3. Self-Assembling Mesh Networks of Femto-Scale Seismic Sensor Motes

In our 2019 report, we described the development and testing of sub-100 gram wireless seismic sensor motes for exploring asteroid interiors. In 2020, we investigated applying the same technology to lunar seismic studies. By leveraging low-mass, low-power MEMS sensors developed for terrestrial oil and gas exploration, a 21st century version of the Apollo Active Seismic Experiment could be conducted with far greater unit sensitivity and a vastly denser and more expansive network of sensors, enabling detailed assays of the sub-surface properties beneath a landing site. Instead of relying on explosive charges to generate seismic signals as in the Apollo era, the sensitivity of the modern sensors enables the exploitation of active seismic signals generated by planned surface activities, including rover driving, drilling, hammering, or takeoff of a crew capsule. Key to the efficiency of these systems is using mote-to-mote communication to enable extremely low-power operation, even within a seismic network that stretches far beyond the local line of site from any central processing hub (e.g., an astronaut, rover, or lander). In 2020, team members (in their homes) designed and assembled a variant of these sensor motes to test self-assembling wireless mesh architectures for their utility in high data rate acquisition in dense seismic networks. These variants were adapted for human or rover deployment, using a ground spike for anchoring rather than the low-g magnetic anchors used in the asteroid variants developed in 2019. We successfully deployed a 9-node system (Figure 2; 8 sensor motes and one ground station) that recorded and transmitted live seismic data across a mesh network from all nodes to a ground station (beyond the line of site from many of the nodes), and tested the resiliency of the network to node failure and introduction of new nodes.

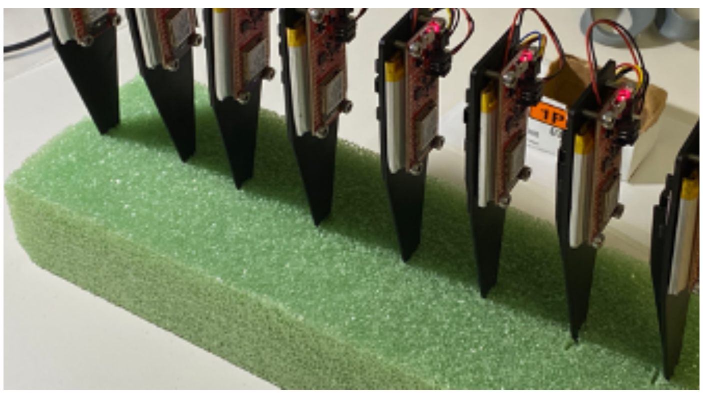


Figure 2: Eight ground-spike seismic sensor nodes, each mesh-networked to the other.

1.4. Suborbital Demonstration of Clockwork Starfish Regolith Sampling System

In 2018, the Project ESPRESSO team conducted a series of experiments that demonstrated magnetic means of collecting asteroid regolith in reduced gravity onboard the NRC-CNRC Falcon 20 reduced gravity research aircraft. In 2019, our team integrated the magnetic regolith collection concept into a full sampling system, the Clockwork Starfish. We proposed to the NASA Flight Opportunities program for a launch to test this regolith sampling system in the long-duration microgravity provided by a Blue Origin New Shepard suborbital flight, hosted in a pair of twin vacuum chambers to enable a technology demonstration in a truly relevant gravity and pressure environment. The proposal was selected, and the Project ESPRESSO Clockwork Starfish were to fly in early 2020. COVID-19 resulted in launch delays, but the Clockwork Starfish eventually flew on October 13th onboard the NS-13 New Shepard launch.

The Clockwork Starfish concept is a tetrahedral microsatellite with a magnetized exterior surface. Deployed by the dozen onto the surface of an asteroid, their magnetized surfaces passively collect regolith. After sufficient regolith has collected, the Starfish evert – that is, they turn themselves inside-out and confine all the regolith stuck to their exteriors inside their new interior. During this eversion process, they expose thruster ports that enable a ballistic hop to high altitude where a waiting parent spacecraft can collect and stow them (and their collected samples) for return to Earth. By relegating the riskiest mission phase – touch down and sample collection – to numerous, extremely simple microsatellite-scale landers, a future asteroid sample return mission could safely sample from numerous sites on a single asteroid, or numerous sites spread across any number of asteroids. A mission architecture like that illustrated in Figure 3 would enable low risk, low cost, multi-site, multi-target sample return from near-Earth asteroids.

> The demonstration sampler collected and stored nearly 50% of its own dry mass in simulated asteroid regolith.

The twin free-flying samplers demonstrated by our team in October 2020 were subscale prototypes of the sampling system alone. They were developed and implemented largely by team members in isolation during COVID-19

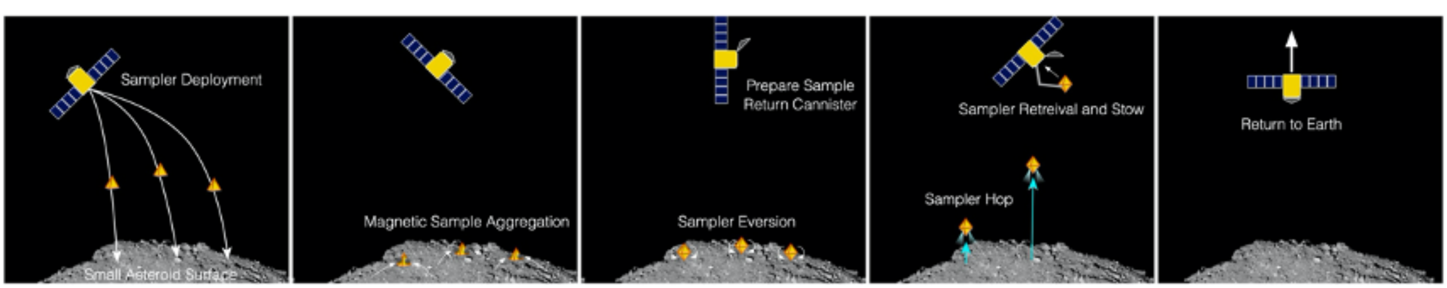


Figure 3: Concept deployment and retrieval of Clockwork Starfish-like asteroid sample return system.

Figure 4: Images from the October 2020 New Shepard launch and demonstration of the Clockwork Starfish sampling system. Top left: The two flight units of the free-flying Clockwork Starfish magnetic regolith sampling systems. Each sampler masses approximately 65 grams. Top right: The BORE-II experiment carrying the Clockwork Starfish to space. Twin acrylic vacuum vessels visible, with Starfish mounted in their launchers and charging cradles visible in the tops of each chamber. Right middle: The two prepared regolith beds, both composed of CI-chondrite asteroid regolith simulant provided by the Exolith lab. One bed was prepared with fine grained material (<2 mm) and the other with larger grained material (2-10mm). Bottom right: The Starfish that completed eversion, showing its interior nearly completely full of collected regolith. Bottom left: Launch of the New Shepard rocket carrying BORE-II and the Clockwork Starfish on October 13, 2020.

lockdown, and some flight components were assembled at team member homes. They contained the systems necessary to support the collection of regolith onto their magnetized surfaces, evert, and store the collected samples through landing and recovery of the New Shepard capsule. The samplers were both successfully fired into prepared beds of simulated asteroid regolith during the microgravity phase of the capsule's flight. After interacting and agglomerating regolith onto their magnetized exteriors for approximately 30 seconds, both samplers attempted eversion. One sampler failed to evert completely due to a long-term storage related issue. The other sampler completed the entire eversion maneuver successfully, turning itself inside-out and confining the regolith it collected in its interior. The successfully-everted sampler collected and stored nearly 50% of its own dry mass in regolith, a remarkably high mass fraction for any asteroid surface sampling system, and one that can be increased by simply making the sampler larger (of order 1U in scale). Our team is currently working to define requirements for future tests of the Clockwork Starfish system, including testing ranges of candidate asteroid surface materials to determine their performance throughout the population of NEOs.

2. Inter-team/International Collaborations

2.1. GEODES Team Collaborations

Project ESPRESSO team members collaborated with GEODES team members to develop requirements for the reduced gravity brazil nut effect experiment described in preceding sections, to be compared against numerical modeling outcomes generated by the GEODES team. These experiments are pending the resumption of the Project ESPRESSO reduced gravity flight campaigns.

2.2. NRC-CNRC Flight Research Laboratory

All development of lightweight vacuum chamber systems for operation in reduced gravity aircraft is being conducted in collaboration with Canada's NRC-CNRC Flight Research Laboratory, as their Falcon 20 reduced gravity research aircraft is our primary platform for lunar- and microgravity experiments.

3. Public Engagement Report

Project ESPRESSO's in-person public engagement efforts (the Maker Explorer workshops and deployments of the Tactile Telescope System) were not deployed in 2020 due to COVID-19 concerns. The Open Telerobotics Rover, designed to enable classrooms to access remote field sites along with our team, was procured in 2020 and tested by solitary team members. Remote operations were demonstrated, along with rich data feeds including high-definition video. Our team is prepared to support deployments of the rover, enabling members of the public to virtually explore our field sites through the eyes of the rover, as soon as field campaigns may resume.

4. Student/Early Career Participation

Undergraduate Students

1. Zane Meyer, UTSA. Zane has assisted team members Soto and Whizin in the development of medium-velocity gas-free projectile launchers for use in vacuum environments, enabling impact experiments in reduced gravity and vacuum without the interference of launcher exhaust.

Graduate Students

2. Leafia Sheraden-Cox, Johns Hopkins University. Leafia previously worked with Project ESPRESSO as an undergraduate through the UNAVCO RECESS program in 2019, where she assisted in the development, calibration, and field-testing of a novel ultra-low cost handheld fluorimeter for mineral identification. She will now continue on related projects as a graduate student at JHU with team member K. Lewis.

Postdoctoral Fellows

3. Dr. Marcella Yant, Johns Hopkins University, Optical Constants and Analog Field Instruments.
   a. First Project ESPRESSO postdoctoral fellow. Led 2019 Palisades field campaign and LIBS/Raman data analysis efforts. Joined 2020 Mini Desert RATS campaign at Mojave Lava Tubes. In March 2020, Dr. Yant left JHU to start a new position as a Planetary Research Scientist at Lockheed Martin in Littleton, CO.

New Faculty Members

4. Professor Sarah Hörst, Project ESPRESSO Co-I at Johns Hopkins University, was awarded tenure and promoted to associate professor.

6. Mission Involvement

No Project ESPRESSO team members' flight mission involvement in 2020 was predicated upon previous SSERVI research. However, ongoing Project ESPRESSO experimental efforts complement multiple team members' involvement in OSIRIS-REx (including micrometeoroid ejecta and thermal fracturing ejecta from Bennu-like regolith experiments; team members Walsh and Molaro). The NASA Flight Opportunities Program selection of BORE-II and the Clockwork Starfish demonstrators (team members Durda, Parker, Whizin) to fly aboard a Blue Origins New Shepard rocket in 2020 was predicated upon the Project ESPRESSO 2018 reduced-gravity demonstration of magnetic sample collection technology and development of the Clockwork Starfish sampling system in 2019 and 2020. Two Project ESPRESSO-developed instruments were submitted to the PRISM RFI, including one led by Co-I Soto that would enable characterization of very high velocity grains ejected by rocket plumes, and another by Co-I Parker that would enable very dense, very expansive networks of seismic sensors to be deployed near landing sites to conduct assays of the subsurface using active seismic signals generated by lander operations.

7. Awards

Professor Sarah Hörst, Project ESPRESSO Co-I at Johns Hopkins University, was awarded a 2020 James B. Macelwane Medal by the American Geophysical Union.

Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES)

Nicholas Schmerr
University of Maryland, College Park, MD

CAN-3 TEAM

1. GEODES Team Report

During 2020, the GEODES team spent its first year preparing datasets, developing a toolbox of geophysical detection tools, and defining exploration methods to characterize a suite of natural resources (lava tubes and void spaces, regolith, ice deposits, and magma-tectonics) that address our goal of enabling in-situ resource utilization (ISRU) at the Moon and other airless bodies of the Solar System. Although the past year presented many challenges owing to the global pandemic, including loss of our initial field activities and collection of pilot datasets, the GEODES team was highly productive, and contributed over 36 abstracts to multiple planetary science conferences and workshops, participated in at least 8 white paper activities involving definition of the future science of lunar and planetary exploration, and helped to assemble geophysical datasets from pre-existing planetary analog research efforts to put our science and exploration activities underway.

1.1. Terrestrial Analog Studies of Geophysical Methods in Volcanic Fields

Terrestrial studies of volcanic fields have long been used to train astronauts and glean insight into the process of basaltic volcanism, which is commonplace throughout the Solar System. Geophysical approaches were incorporated into the Apollo program, have been prevalent in robotic missions, and will continue to be invaluable to future crewed missions under Artemis. GEODES is building off the work of our precursory PSTAR-funded projects, GILA-MONSTER and TUBE-X that collected a series of seismic and magnetic studies from two planetary geophysical analog localities that inform lunar exploration science across our ISRU themes.

1.1.1. San Francisco Volcanic Field - Flagstaff, Arizona

One of the GEODES field sites is at the San Francisco Volcanic Field (SFVF), Arizona. In October 2019, at the beginning of our first year, GEODES team members, including Nick Schmerr, Jacob Richardson, Ernie Bell, Patrick Whelley, Ryan Porter, and Renee Weber spent two weeks collecting a range of seismic, magnetic, geochemical, and LiDAR datasets that are now in use by the GEODES team (Fig. 1).

Figure 1. GEODES team geophysical data collection activities at Cinder Lake (top), where we collected active source seismic data, and Lava River Cave (bottom), where we collected magnetometer, seismic, and ground-penetrating radar data. Both sites are within the vicinity of the SFVF near Flagstaff, AZ. Photos by N. Schmerr.

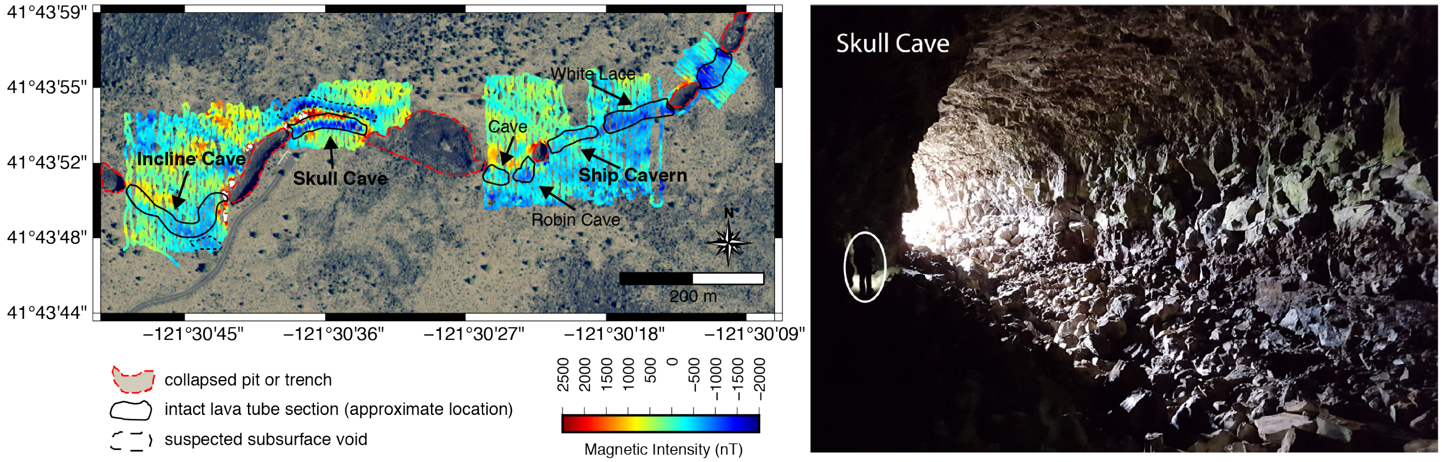


Figure 2. The GEODES team is using a suite of datasets from our precursor projects, here the TUBE-X project by Co-I Kelsey Young. The map shows the surface magnetic anomaly observed by a ground-based total field magnetometer survey of the Modoc Crater lava tube system in LBNM. LiDAR-derived tube subsurface geometry are shown in the black outlines. Collapse pits are indicated by broken red lines, and the magnetically inferred location of an unexplored subsurface tube is in broken black lines. Internal picture of Skull lava tube shown to the right with person circled for scale. Photos by E. Bell.

On that field expedition, we recreated the geometry of active sources and stations of the Apollo 17 Active Seismic Profile Experiment in Cinder Lake, a past location of Apollo astronaut geological training, and examined the efficacy of instrument burial in regolith (in this case cinders). The data are being used to determine the accuracy associated with relocating thermal moonquakes detected on the Apollo 17 array and generate requirements for future missions.

We also collected geophysical data on two lunar regolith simulants localities, the Blackpoint Lava Flow (source of BP-1) and a Merriam Crater cinder quarry, the source of JSC-1. A little serendipity was at play for our team, as the Merriam Crater quarry was owned by our AirBnB host who generously provided us with full access to this classic simulant locality. The associated samples and geophysical signatures are being used to create a rock physics model for characterizing geophysical simulant materials in the laboratory.

We were also able to collect magnetic profiles, LiDAR, and two seismic active source surveys over Lava River Tube, a 1.5 km lava tube in the region. Such studies are relevant to understanding the upcoming landed missions, including Artemis at the South Pole, the Lunar Geophysical Network, and CLPS missions to Reiner Gamma and Schrödinger basin on the Moon, and determine the relationship between pyroclastic deposits, melt sheets, and local graben and fractures.

1.1.2. Lava Beds National Monument - California

The GEODES project has a second field site in Lava Beds National Monument (LBNM), CA, where our precursor project TUBE-X, led by Co-I Kelsey Young, has completed magnetic surveys and LiDAR mapping of lava tubes to study the ability to geophysically detect and characterize tube structure and spatial extent. A Fall 2020 pilot field season to expand upon this dataset and capture several joint datasets has been delayed until travel becomes available again in 2021. Data analysis of the precursory magnetic survey collected by GEODES PhD graduate student Ernie Bell reveals a linear correlation between the strength of the lava tube magnetic anomalies and the geometric ratio of tube depth and cross-sectional area (Fig. 2). His ground-truth benchmarking indicates that the magnetic method can be translated to the Moon for evaluating lunar lava tubes as targets for additional study and exploration and was presented in a Lunar and Planetary Science Conference abstract (Bell et al., 2020). The field methods employed in these studies can be evaluated for aspects that are best suited for automation, remote monitoring, or crew executed/tended for lunar exploration.

1.1.3. Online Planetary Analogs Geophysical Database

The GEODES Field Data Group, led by Co-I Patrick Whelley, has amassed over 103 GB of geophysical data collected by precursory projects and complementary efforts led by members of the GEODES team. The new database is searchable and linked to a data depository with full documentation of datasets in a Digital Repository archive at the University of Maryland (Fig. 3). GEODES is working

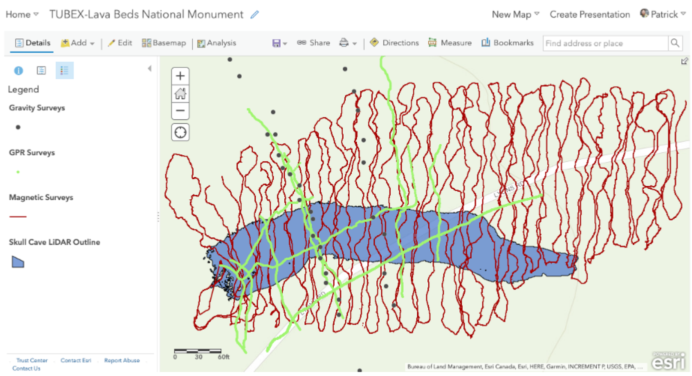


Figure 3. Example database of geophysical datasets that has been created by the GEODES team. ArcGIS online map shows the LiDAR-derived outline of Skull Cave (blue), GPR (green), magnetic (red), and gravity surveys (black dots). Data were collected by TUBEX PSTAR team lead Kelsey Young.

with data from predecessor and collaborative projects (TUBEX, GILA-MONSTER, GIFT) to build discoverable and searchable data archives and online maps of planetary analog geophysical observations. Current databases include the San Francisco Volcanic Field near Flagstaff, AZ (Section 1.1.1), and the Modoc Crater Lava Tube System in Lava Beds National Monument, CA (Section 1.1.2). Data are searchable and linked to our data depository with documentation and datasets in the GEODES Digital Repository archive at the University of Maryland. Other data portals that we have in mind for community-valuable data are the PDS, USGS ScienceBase, and Earth Trek. The goal of this GEODES activity is to help the team work with new and old data, plan for future field expeditions, and make the data highly accessible to SSERVI and the planetary exploration community.

1.2. Joint Geophysical Inversion Methods

Geophysical methods at the lunar surface will be a key component of identifying buried geologic units and characterizing the lunar ISRU targets. In order to make full use of multiple geophysical datasets, joint inversion schemes are necessary for extracting maximal information. GEODES Postdoctoral Fellow Dr. Doyeon Kim is developing an active seismic imaging approach that can maximize the full range of seismic waveform data while quantifying uncertainties of inferred subsurface properties. From this foundation, he has created an inversion framework that enables straightforward incorporation of complementary geophysical datasets including seismology, gravity and magnetic field data. His approach is a hybrid, waveform inversion method called Epicycle Waveform Information Extraction (EWIE) for obtaining subsurface information from seismic waveforms (Fig. 4). The algorithm is based on a trans-dimensional Bayesian inversion of both body and surface wave measurements, along with accurate

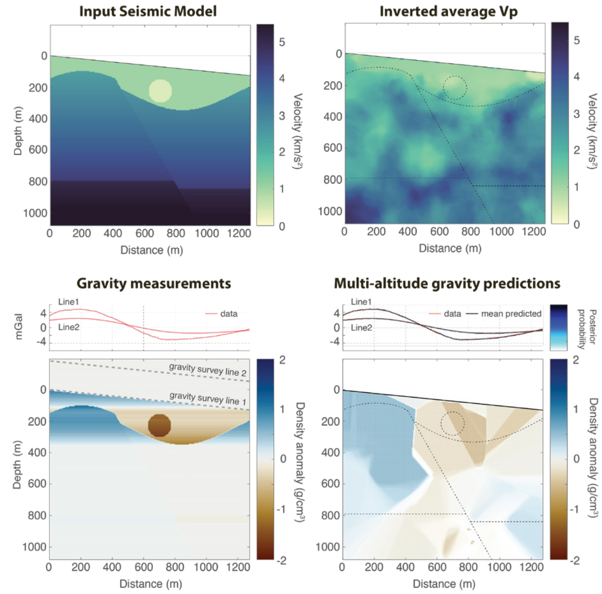


Figure 4. The GEODES team has developed new tools for performing joint inversions across different geophysical datasets. Top Panels: Seismic model and mean inverted Vp and Vs models using both P and S arrival times using the EpiGE algorithm. Bottom Panels: Input models and predicted data and mean inverted density anomaly for multi-altitude gravity measurements.

waveform predictions using a 2D pseudo-spectral method. Since full waveform simulations are computationally expensive, individual iterations are sped up by using multiple levels of approximation, including 1D surface wave kernels, 3D ray-tracing methods, and linearized travel-time predictions. His Voronoi parameterization of the model can recover complex geometries while allowing straightforward extension to other geophysical datasets. As a first step, he has tested the approach with a synthetic target model that mimics observed geological features as well as the geometry of an active seismic survey carried out in one of the GEODES field sites at the San Francisco Volcanic Field in Flagstaff, Arizona, presented at the Virtual Fall Meeting of the American Geophysical Union (Kim et al., 2020). The development of the joint, full waveform inversion method and its validation in a planetary analog environment will inform capabilities and field strategies in future geophysical explorations of planetary bodies including upcoming lunar science missions.

1.3. Lava Tube Stability Modeling

The presence of lava tubes on the Moon and other planetary bodies has been inferred from the observation of skylights and collapse pits that provide glimpses of void space in the subsurface. Lunar lava tubes are postulated to have dimensions significantly larger than those observed on Earth and are regarded as potentially valuable assets that could host long-term lunar bases. The

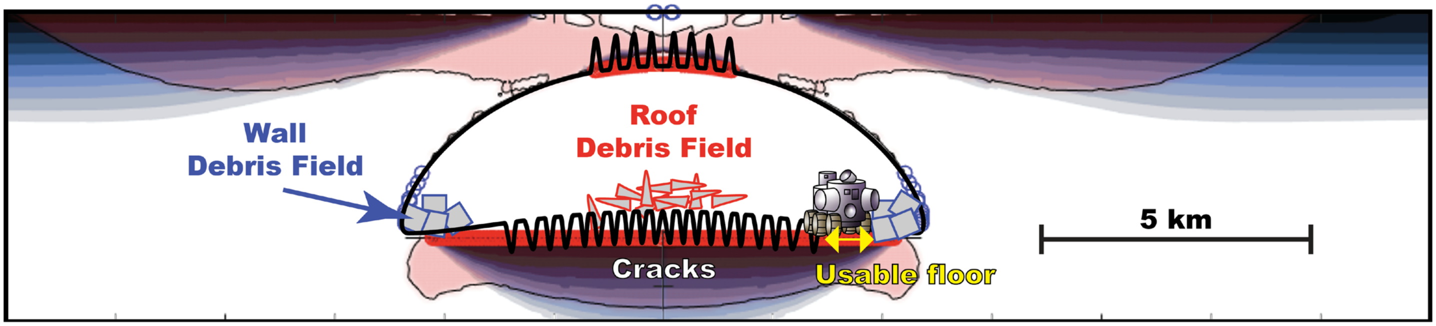


Figure 5. Interpretation of numerical models produced by the GEODES team for the stress field around a lunar lava tube. Due to the large size of lunar tubes, tension along the roof and the floor (red shading) lead to cracking, while compressive failure can occur at the base of the walls (blue circles). Only a small portion of the floor may be considered intact, that is, devoid of cracks and debris from failure at the roof or the walls and would therefore be best suitable for exploration activities.

GEODES team is developing ways to deduce the location of lunar lava tubes from observable surface features and determine their internal characteristics, such as width, depth, and use tube geometry to infer how much of the tube has undergone tensile or compressive failure to evaluate tube stability and exploration potential. GEODES graduate student, Edward Williams has been developing an elastic Finite Element Model of an idealized lava tube, which adopts lunar gravity and material characteristics. Only gravitational loading of the tube by the weight of the rock above and surrounding it is considered in their model at this point. Lava tube widths and depths are varied and models were repeated assuming Earth's gravity to compare to terrestrial lava tubes. The stresses on the rock produced in these models were analyzed to determine where tensile and compressive failure was expected to occur, both along the walls of the tube and at the surface, where they could be examined by geophysical techniques before exploration of the tube.

In all models, the surface bows down over the tube, but an elastic bulge develops some distance away from the tube center (Fig. 5). The distance from the center of the lava tube to the summit of the bulge is always 1.8 ± 0.2 times the distance from the center of the tube to the maximum surface stress. Therefore, if a surface bulge and an area of high stress on the surface, perhaps highlighted by cracks, is observed, this relationship could be used to locate the tube causing them. The extent of tensile failure on the surface depends approximately linearly on tube width; this could be useful for deducing the width of a concealed tube. All lunar models that have tensile failure on the tube floor show that it affects over 65% of the floor; in most cases, over 80% is affected. However, no failure is expected on the floor of a lava tube that has the smaller dimensions of those observed in terrestrial lava flows. The extensive fracturing of lunar lava tube floors presents challenges for space exploration and use of these tubes as long-term bases. Fractures also may provide stable locations to house volatiles trapped within the tube itself.

1.4. Particle Interaction "Brazil-Nut Effect" Modeling

The GEODES team had investigated how seismic shaking caused by nearby impacts can cause the upward migration of boulders in regolith materials. This has been termed the "Brazil nut effect" or BNE, which results in the largest clasts in a mixture moving upward through smaller particles and ending up on the surface (as in a jar of mixed nuts). This effect could bias interpretation of surface rock populations on SSERVI target bodies such as the Moon, and influence our interpretation of regolith physical processes. GEODES PhD graduate student Joe DeMartini has developed a successful approach to simulating rubble piles using the discrete element method (DEM), which uses individual (typically spherical) particles to represent the constituent blocks of the rubble pile, with particle properties chosen to mimic bulk properties of real materials, such as angle of repose (Fig. 6). Particles that make up real granular materials, however, are most often not spherical. The shapes of real grains make it more difficult for them to slide past one another, can create quasi-stable equilibria when grains are vertically stacked, and cause granular media to "bulk" under shear (creating more void space and less efficient packing). The aim of Joe's work is to develop a new algorithm for handling simulations using large numbers of irregularly shaped particles with pkdgrav, a DEM code that has been used effectively to model granular dynamics on rubble piles and show that simulations with irregularly shaped grains can lead to results more akin to real granular systems. Our preliminary results from this GEODES investigation shows that when simulating with irregular grains, interparticle friction makes the BNE less efficient and thus the brazil nut rises slower, in contrast with results of simulations using spherical grains. Natural clasts tend to have irregular surfaces, with our result implying that

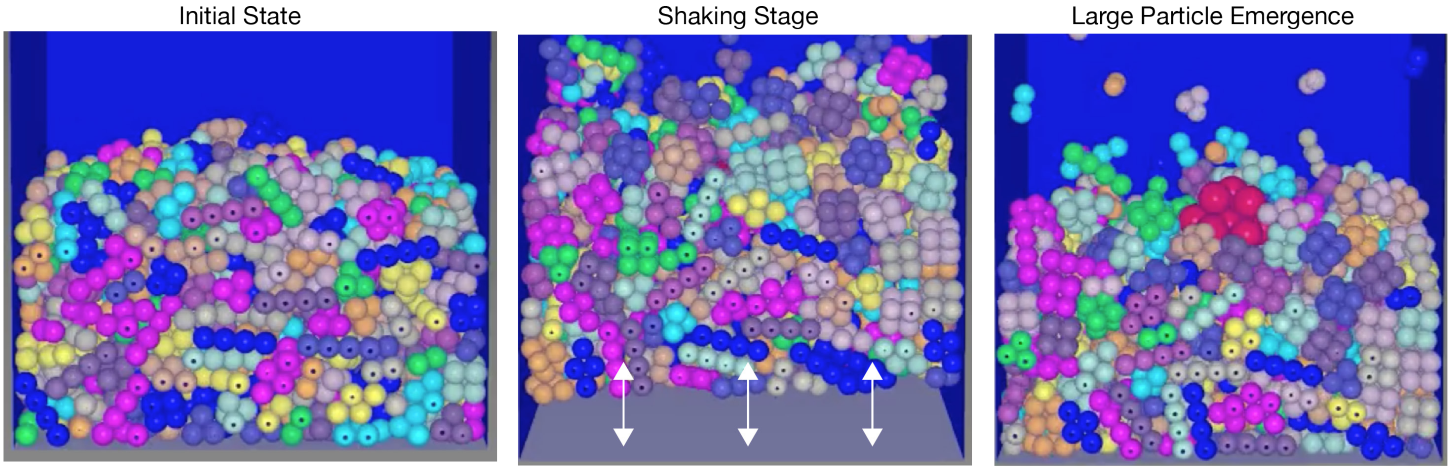


Figure 6. The GEODES team has simulated BNE conditions on the Moon using irregular particle shapes to ascertain the importance of grain shape on the rise speed of the buried body. Attached is a snapshot from a simulation of the Brazil-nut Effect in lunar gravity using the parallel N-body gravity tree code pkdgrav. A ~1.5 cm diameter polyhedral body (the "Brazil-nut," seen in red) begins at the bottom of a walled container with a 10 x 10 cm^2 base, surrounded by almost 2000 ~0.7 cm diameter polyhedral bodies. The medium is shaken sinusoidally with frequency and amplitude chosen such that the equivalent acceleration is 3 times the ambient lunar gravitational acceleration.

these features must have undergone significant amounts of shaking to bring larger particles to the surface of the regolith.

2. Inter-team/International Collaborations

2.1. A Probabilistic Seismic Hazard Assessment for the Moon (GEODES/TREX)

The GEODES team has partnered with the TREX team to construct a probabilistic seismic hazard assessment (PSHA) for future lunar exploration. This partnership includes Maria Banks (NASA-GSFC/TREX), Lisa Schleicher (USGS/GEODES), Shelby Bensi (UMD/GEODES) and Tom Watters (SI/GEODES). In this new inter-team collaboration, we are exploring the application of PSHA methods used in the nuclear industry to selected test sites on the Moon. For our study we are developing a seismic source model, ground motion model, and site response model to estimate the seismic hazard at selected test sites on the lunar surface near recent areas of seismic shaking. The PSHA takes advantage of the global coverage of high-resolution images and altimetry data from the Lunar Reconnaissance Orbiter (LRO) spacecraft that have enabled detailed mapping of tectonic features on the Moon, including lobate scarps, wrinkle ridges, and graben. The identification of young and active fault scarps is then being combined with our understanding of the impact crater production rate, evidence for and characteristics of recent activity along faults (crisp morphologies, cross-cutting relationships with small craters, associated small-scale graben, crater-size frequency distribution analyses of surfaces surrounding the faults), newly developed lunar seismic ground motion scenario shakemaps, and data from the Apollo-era seismic network on the nature of the subsurface. These data and information collectively offer the components needed to develop a preliminary probabilistic seismic hazard analysis (PSHA) for the Moon. Dr. Lisa Schleicher presented results from this study at the Lunar and Planetary Science Conference and Virtual NASA Exploration Science Forum, and Dr. Maria Banks presented the work at the Virtual Fall Meeting of the American Geophysical Union.

> A Probabilistic Seismic Hazard Assessment is a tool used to evaluate the threat that ground shaking from moonquakes and meteoroid impacts onto the lunar surface poses towards future habitats, infrastructure, and human astronaut crews. A PSHA is essential for designing building codes for the engineering and construction of infrastructure that would enable a human presence on the Moon.

2.2. Joint Field Expedition with Other SSERVI Teams

Although field work was canceled due to the COVID-19 pandemic in 2020, the GEODES team has planned to join the RISE2 team in the Potrillo Volcanic Field in New Mexico. Our goal is to conduct a 2-D seismic, gravity, GPR, and magnetic profile of the Kilbourne Hole Volcanic Crater to determine the nature of the subsurface dike that supplied the eruption with magma. The surveys will be designed to be analogous to a similar survey on the Moon and serve as an opportunity to familiarize astronauts and participants with geophysical equipment and active sounding techniques. While the initial expedition date was scheduled for Spring of 2020, this collaboration persists as we wait for the end of the pandemic. Once travel becomes available to the teams, GEODES and RISE2 plan to rekindle this new inter-team partnership and collaboration between our two SSERVI teams. Note that the data generated by these activities will be shared between teams in our Online Planetary Analogs Geophysical Database and Digital Repositories at the University of Maryland (see Section 1.1.3).

2.3. NASA Planetary Analogs Website

The GEODES Public Engagement team has partnered with RISE2 to develop content for a new webpage on the NASA Solar System website, https://solarsystem.nasa.gov/, specifically for planetary analog field research. This new page will explore different aspects of planetary analog research through a process perspective (i.e., through topics including “volcanology” and “tectonics”) and by giving real life field work examples. This public resource, led by GEODES Co-I Nicole Whelley with help from RISE2 SA/CS/PE Lead Caela Barry, will be published to the public-facing website in early 2021.

3. Public Engagement

GEODES public engagement introduced thousands of interested members of the public to field geophysics and the Moon in our first year, as we transitioned from Out-of-Doors to Stay-at-Home.

3.1. Engagement in the Field

Between the first weeks of the GEODES project and February 2020, we shared field experiences with the public. During November 2019, our field expedition to Flagstaff, Arizona (Section 2.2.1) “took over” official social media accounts for NASA Expeditions, introducing an audience of thousands to performing science investigations in the volcanic analog field environments surrounding Flagstaff. Tweets and posts on Facebook highlighted our team and our science, including magnetic surveys, laser scan mapping, and seismic surveys over lava tubes and within volcanoes. This included a recreation of the Apollo 17 Lunar Seismic Profiling Experiment in the Apollo Astronaut training grounds in Cinder Lake Hills, near Flagstaff, AZ. Our takeover drew 139,000 impressions on Twitter and 18,000 on Facebook. See the Twitter collection here: https://twitter.com/i/events/1240648363630084102.
In February, our Public Engagement lead, Molly Wasser, and Deputy P.I. Jacob Richardson, supported the Death Valley Dark Sky Festival that drew 3,000 visitors over a weekend in the Death Valley National Park. This annual festival celebrates all things space and the GEODES team led tours that connected sites at Death Valley to similar points of interest in the Solar System. Molly Wasser helped lead a tour of Mars Hill, which was a test site for the Mars Viking lander, and managed a booth with activities and resources at the Death Valley Visitors Center. Jacob Richardson led tours of Ubehebe Crater, a volcanic crater similar to those found on the Moon that are a focus of the GEODES Magma-Tectonics Theme.

3.2. Virtual Engagement

As the world went virtual, GEODES public engagement pivoted to produce high-quality online experiences during 2020. The GEODES website was designed and is now hosted at https://geodes.umd.edu. This site will serve as a portal for public access to our team’s data, STEM videos and demonstrations, and information about our team and research. Co-Is at the University of South Florida, Chuck Connor and Laura Connor, have been developing

interactive geophysics models that show how magnetic and gravity anomalies change when features in the subsurface change with a click of a button.

Our engagement team, led by Molly Wasser, supported two successful online-only events celebrating space science. First, International Observe the Moon Night was September 26th, and included pre-recorded videos and a live broadcast, which GEODES public engagement lead Molly Wasser emceed. This night included a trashcan video demonstration recorded by Molly Wasser and Jacob Richardson, with a cameo by RISE2 engagement lead Caela Barry. Despite the pandemic, over 3,000 socially-distanced events and observers registered for the event. Following this event, our team members supported the Red Sox STEM Day on September 29th, which was a partially live event that showed pre-recorded videos, including the trashcan volcano demonstration, and answered live questions from the internet.

4. Student/Early Career Participation

In the first year of the GEODES project, our team grew significantly, adding 15 new science collaborators that span the early career spectrum. At least one undergraduate (Kris Laferriere, working with Dr. Jessica Sunshine in Astronomy) has gone on to start a graduate career in planetary science. This diverse group of new team members is collaborating across the team's various resource themes (identified below), has built GEODES connection to other SSERVI teams, and has expanded our geophysical expertise to new realms of research.

Undergraduate Students

1. Kris Laferriere (Astronomy, advisor: Jessica Sunshine), University of Maryland, Ice Deposits, calibrated, optimized the thermal removal, and analyzed Deep Impact data collected over the Moon's South Pole (now studying planetary science at Purdue University w/ Dr. Ali Bramson).

Graduate Students

1. Edward Williams (Geology Masters candidate, advisor: Laurent Montési), University of Maryland, Tubes/Voids, Magma-tectonics Themes, modeling of fracture occurrence and density within lava tubes on the Earth and the Moon.

2. Brianna Mellerson, (Geology Masters candidate, advisors: Ved Lekic and Nick Schmerr), University of Maryland, Tubes/Voids Theme, magnetic and gravity modeling of lava flows.

3. Ernest Bell (Geology PhD candidate, advisor: Nick Schmerr), University of Maryland, Tubes/Voids, Magma-tectonics Themes, geophysical field techniques and operations, modeling of lava tubes and subsurface tectonic structure.

4. Joseph DeMartini (Astronomy PhD candidate, advisor Derek Richardson), University of Maryland, Regolith Theme, computer simulations of shaking and the Brazil Nut Effect for asteroids and the Moon.

5. Casey Braccia (Geology PhD candidate, advisor Wenlu Zhu), University of Maryland, Volatiles Theme, Ice Deposits, Tube/Voids Themes, rocks physics experiments with planetary surface materials and microtomographic imaging of pore space.

6. Linden Wike (Geology PhD candidate, advisor Nick Schmerr), University of Maryland, Tubes/Voids, Ice Deposits, Regolith Themes, seismology and wave interactions with pore space and cavities, scattering and wave propagation simulations.

7. Yisha Ng (Mech. Eng. PhD candidate), Arizona State University, Tubes/Voids Theme, engineering and field instrumentation design and operations.

Postdoctoral Fellows

1. Doyeon (DK) Kim, University of Maryland, Tubes/Voids, Magma-tectonics, Regolith Themes, joint inversion methods, seismology and forward wave propagation models.

2. Sajad Jazayeri, University of South Florida, Regolith Theme, ground penetrating radar data analysis and modeling of void space GPR signatures.

New Faculty Members

1. Michelle (Shelby) Bensi, University of Maryland, Magma-tectonics, lunar probabilistic seismic hazard analysis modeling.

2. Lisa Schleicher, US Geological Survey, Magma-tectonics, lunar probabilistic seismic hazard analysis modeling.

3. Tom Watters, Smithsonian Institution, Magma-tectonics, lunar tectonics and fault mapping.

4. Maria Banks (TREX), Goddard Space Flight Center, Magma-tectonics, fault scrap mapping and fault process modeling.

5. Harry Lisabeth, Lawrence Berkeley National Laboratory, Ice Deposits, Regolith Themes, micro-scale acoustic experiments and geophysical properties of sample.

Promotions

- In June, GEODES P.I. Dr. Nicholas Schmerr was promoted from Assistant Professor to Associate Professor with tenure in the Department of Geology at the University of Maryland, College Park.

- In January, GEODES Deputy P.I. Dr. Jacob Richardson was promoted from Postdoctoral Associate to Assistant Research Scientist at the Department of Astronomy at the University of Maryland, College Park.

5. Mission and Instrument Involvement

GEODES Activity Associated with Mission Development
1. Lunar Geophysical Network (New Frontiers-5; Planetary Mission Concept Study), Nicholas Schmerr, Seismometer Experiment, Role: Co-I; Matt Siegler, Heat Flow Experiment, Role: Co-I; Renee Weber, Seismometer Experiment, Role: Deputy-P.I. Work by members of the GEODES team is helping to refine the deployment strategies for the mission and creating data analysis tools that inform on the LGN science goals and expected science return from the mission. In particular, the GEODES planetary analog work (see Sections 1.1.1-1.1.3 above) and modeling efforts provides data that is being used to create instrument requirements and test deployment strategies and will be used in the full mission proposal. The report of the LGN Planetary Concept Mission Study can be found at: https://science.nasa.gov/solar-system/documents.

GEODES Activities Associated with Instrument Development

2. Lunar Environmental Monitoring Station (LEMS; DALI), Nicholas Schmerr, Seismometer Instrument, Role: Co-I; GEODES is providing opportunities for instrument field testing to the project and enabling analog experiments to determine deployment strategies for the seismometer instrument.

3. SUBsurface Lunar Investigation and Monitoring Experiment (SUBLIME; DALI), Nicholas Schmerr, Seismometer Instrument, Role: Co-I; Terry Hurford, Seismometer Instrument Development, Role: P.I. GEODES is providing opportunities for instrument field testing to the project and enabling analog experiments to determine deployment strategies for the seismometer instrument.

4. Seismometer for a Lunar Network (SLN; DALI), Nicholas Schmerr, Seismometer Instrument, Role: Co-I; GEODES is providing opportunities for instrument field testing to the project and enabling analog experiments to determine deployment strategies for the seismometer instrument.

Interdisciplinary Consortium for Evaluating Volatile Origins (ICE FIVE-O)

Jeffrey Gillis-Davis
Washington University, St. Louis, MO

CAN-3 TEAM

1. ICE FIVE-O Team Report

Team ICE Five-O investigates volatile origins and evolution, and examines volatile-soil interactions.

1.1 Theme 1: Experiments and Modeling.
This theme will assess, constrain, and predict the physical, spectral, chemical, and isotopic signatures associated with volatile ices, lunar minerals and glasses, and their interactions with each other

1.1.1 Jeffrey Gillis-Davis: ICE Five-O P.I.: Washington University, St. Louis.
Laser weathering of lunar analogs and samples

- The Washington University Physics Department and McDonnell Center for Space Sciences contracted to renovate laboratory space to support laser weathering experiments. Gillis-Davis set up existing lab equipment moved from the University of Hawaii (Fig. 1). In addition, new lab equipment was purchased to upgrade the facility to conduct state-of-the-art laser weathering experiments (e.g., helium compressor, water chiller, UHV vacuum system, and second laser with a long μsec pulse).
- Testing and evaluation of μsec pulse laser to produce agglutinates is in its initial stages. I have created what, to first order, looks like lunar agglutinates. In FY2, these samples will be passed on to Co-I Andrew Ichimura for magnetic measurements. Spectra of these samples will be passed along to Co-I Heather Kaluna for spectral analyses in FY2.

The new method for laser space weathering will allow the systematic examination of temperature and volatiles effects on the spectral, physical, and chemical products of space weathering.

Regolith in lunar polar regions is likely to be fundamentally different than regolith from the equator because of the unique microenvironment under which it formed. Hence, NASA will directly benefit from the experimental results, the spectral and analytical measurements, and the methods developed to curate cryogenic samples.

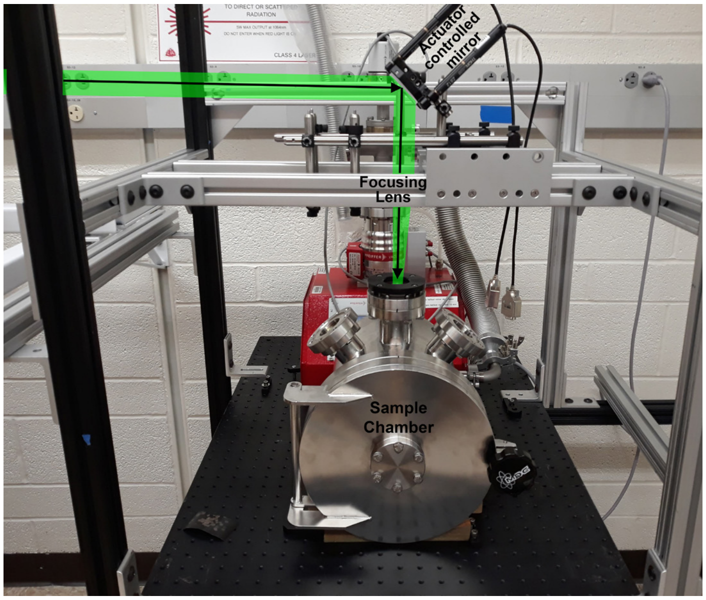


Fig 1. depicts 1065 nm wavelength laser photons being redirected by an actuator controlled mirror, which steers the beam back and forth across the sample. Laser light is focused to a 250-μm spot size by a lens after it is redirected by the mirror. Samples are held in the horizontal plane so that powders can be used.

1.1.2 Gerardo Dominguez: Co-I, Theme 1 Lead: California State University, San Marcos.

Evolution: Radiation processing of Volatiles and Volatile Covered Surfaces

- Completed design, manufacture, and installation of a robust rail system for He cryostat to enable socially distanced (and safer) sample changes in UHV chamber for ICE Five-O proton irradiation experiments.
- Installed NanoInfraRed (IR) system for performing studies of IR spectral properties of samples/targets with 10-20 nm resolutions between (850 cm-1–1900 cm-1). Upgrade to Nano-FTIR for enhanced IR spectral mapping is scheduled to be completed in February 2021. Competing quotes for a dry air delivery system to provide ultra-low H2O vapor backgrounds have been requested and compiled, and acquisition and installation of this system is anticipated for end of January 2021.
- We have demonstrated Atomic Force Microscopy-InfraRed (AFM-IR) Hyperspectral (rapid) imaging of a polished Murchison meteorite section (Fig. 2). We have confirmed Scattering Nearfield Optical Microscopy (SNOM) NanoIR mapping with standards and will be developing expertise to carry out SNOM imaging of meteorite samples this coming year, including Hayabusa samples.

In-situ isotopic measurements of lunar ices must account for isotopic fractionation caused by transport and radiation induced chemical reactions in order to accurately determine volatile source(s).

1.1.3 Parvathy Prem (Co-I): Applied Physics Laboratory

Isotopomer surface lifetimes: Impacts on transport and composition

- Co-I Prem has been mentoring a group of five undergraduate interns at APL who are working on running and analyzing volatile transport simulations to support ICE Five-O science goals, which has led to a submitted LPSC abstract (Alfaro et al., 2021). The abstract presents initial results from a baseline simulation of H2O and HDO, assuming equal desorption activation energies for both species. We find that HDO is less susceptible to thermal escape and more susceptible to photodestruction, likely due to the lower mean thermal velocity of heavier molecules. Initial results suggest that this leads to a very slight overall enrichment in the D/H ratio of cold-trapped water relative to its source. This is a significant result because previous work has arrived at opposite conclusions regarding whether mass differences lead to D/H enrichment or depletion. Our objective here is to illuminate the physical processes that determine this.

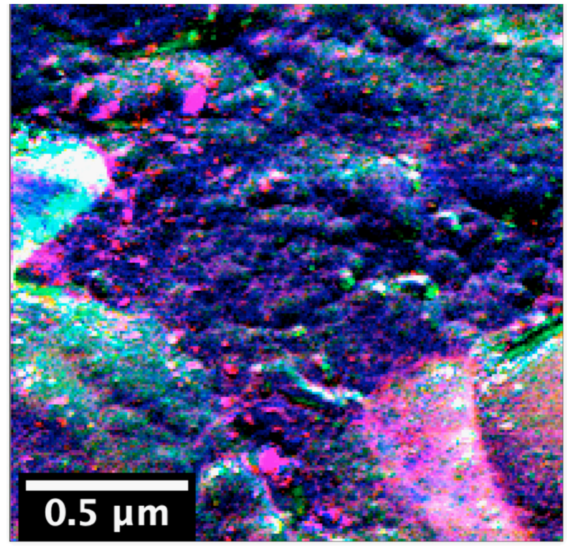


Figure 2. IR composite image of aqueously altered Murchison meteorite with topographical context. Different colors indicate different IR spectral phases present. Note the size of the smallest phases is <100 nm. Image acquired using tapping AFM-IR between 950 cm-1 and 1900 cm-1.

1.1.4 Bradley Jolliff (Co-I) and Alian Wang (Co-I): Washington University, St. Louis

Alteration of lunar samples in response to exposure to volatile deposits

- Researchers worked on design modifications to the Water InfraRed (WIR) spectrometer for use in the Planetary Environment & Analysis Chamber (PEACh) environmental chamber. WIR modifications include new IR emitters for low-temperature vacuum operations, and new IR detector for vacuum operations. Work is ongoing to characterize the new IR emitters, install new IR emitters on WIR-II with new driving circuit, and conduct vacuum tests on the IR detector. In addition, the PEACh chamber is being upgraded to achieve vacuum performance to at least 0.1 mbar.

1.1.5 Edward Cloutis (Collaborator): University of Winnipeg

Detection of lunar ice

- Continued work on a CSA/ESA-funded lunar cubesat mission (VMMO) that will search for ice in permanently-shadowed regions at the lunar south pole at better than 50 m spatial resolution. This will be done using a 3-band LIDAR system operating at 532, 1064, and 1560 nm. Three new projects began as part of CSA's Lunar Exploration Accelerator Program (LEAP). These are Phase 0 studies centered around lunar landers/rovers that will explore for water ice using either infrared spectrometers or an active Raman system.

1.2 Theme 2: Analytical Characterization of Volatile Exposed Materials.

Analytical instruments capable of nm-scale spatial resolution and with high spectroscopic sensitivity are needed to study space weathering owing to the nm-scale dimensions over which it takes place

1.2.1 Hope Ishii: D.P.I., Theme 2 Lead, John Bradley (Co-I), Kenta Ohtaki (Postdoc): University of Hawaii at Manoa.

Electron microscopy on interplanetary dust particles (IDPs) and Theme 1 experimental materials

- An analytical double-tilt cryo-transfer TEM holder was ordered and has arrived. The TEM holder will allow us to prepare frozen samples and keep them frozen during transfer into the TEM and during analysis. This capability enables immobilization and study of volatiles and sensitive organics in native environments.
- Characterization of solar wind-irradiated interplanetary dust particles (IDPs) has begun. IDPs may be potential analogs for regolith in permanent shadow on the Moon. Organics in IDPs are believed to arise from the processing of precursor ices. We are comparing several petrographic environments of organic carbon in chondritic porous IDPs to investigate abundances of heteroatoms that may be inherited from ice chemistry and to assess whether the carbon comes from a single origin or multiple generations of ice (e.g. Fig. 3).
- We have also begun testing our ability to map features of volatile water at the nanoscale in fine-grained lunar soil using electron energy loss spectroscopy (EELS).

1.2.2 Ryan Ogliore: D.P.I.: Washington University, St. Louis

NanoSIMS measurements of Theme 1 experimental materials

- We have developed a technique using peak-jumping and multi-collection NanoSIMS to measure water D/H in samples. We measured H, D, CN, O, and Si with a ~100-nm beam spot in imaging mode and calculated correlations between D/H and the other ions. Measurements of meteorites Renazzo (CR2) and Murchison (CM2) are consistent with literature values. We made measurements of D/H in clasts (Tagish Lake, Murchison) that can be compared to their hosts. Tagish Lake water appears to be more deuterium-enriched than other carbonaceous chondrites (Fig. 4), and much more D-rich than what was inferred by previous mass balance calculations,

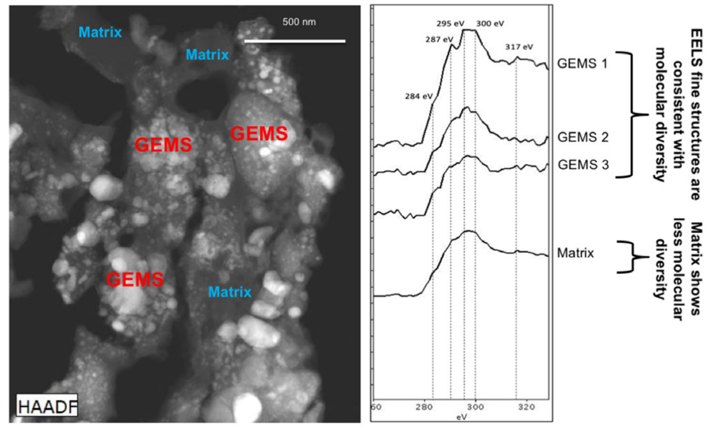


Figure 3. S(TEM) High Angle Annular Dark Field (HAADF) image (left) showing two petrographic environments of organic carbon in chondritic porous IDPs. Organic carbon-amorphous silicate composite grains (GEMS) and organic carbon matrix that binds GEMS together (Matrix) show differences in EELS fine structure at the carbon K-edge (right) that indicate differences in the degree of molecular diversity in their constituent organics.

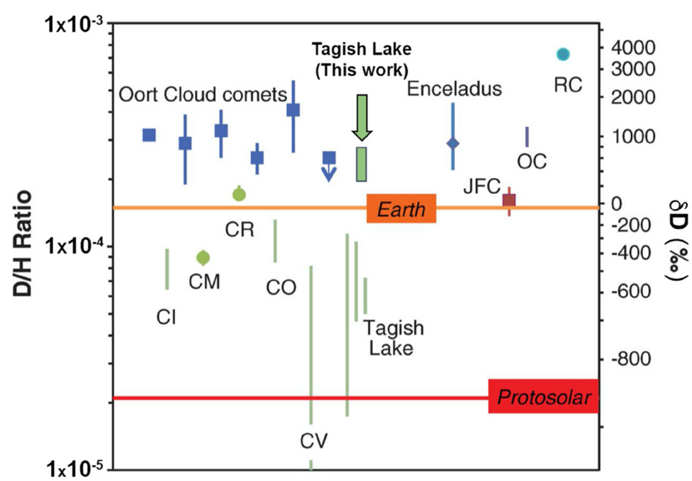


Figure 4. Tagish Lake appears to be more deuterium-enriched than other carbonaceous chondrites (e.g., CI, CM, CO, CV) based on our measurements. This finding is consistent with some cometary water sources, which may have formed in the outer part of the young Solar System (measurements are ongoing).

consistent with Oort cloud comets which may have formed in a similar place in the young Solar System (measurements are ongoing). This technique will be employed to measure lab proton-irradiated samples from Co-I Dominguez and measure D/H in lunar apatite.

1.3 Theme 3: Remote Sensing

Understanding the interplay of reflectance and thermal emission and detection and quantification of organics

1.3.1 Paul Lucey: Co-I, Theme 3 Lead, Abby Flom (graduate student): University of Hawaii at Manoa

Address issues of mixed thermal and reflected signal in infrared spectroscopy and establish detection limits for organic materials.

- Two distinct methods are currently used to separate reflected and emitted radiance in the 3-4 μm region to obtain accurate reflectance spectra in regions where both sources are significant. The first uses spectrally constant emissivity, the second uses Kirchhoff's Law to estimate emissivity. The latter assumption can be used to directly calculate reflectance analytically, but suffers from mathematical singularities and sensitivity to noise when solar and thermal terms are very similar (Fig. 5). Direct comparisons of application of both methods to measured telescopic spectra of the Chang'e 5 landing site on the Moon have been carried out, and were presented in an abstract to LPSC 52, contrasting their strengths and weaknesses.

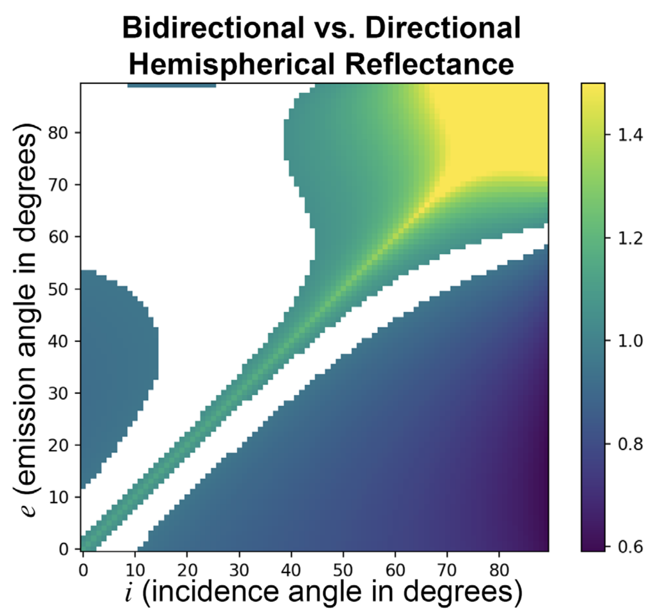


Figure. 5 Illustrates the ratio of bidirectional reflectance to directional hemispherical reflectance with respect to incidence (i) and emission (e) angle viewing geometry. Depending on incidence and emission angles, the ratio varies between about 0.6 and 1.4, which means that assuming they are equivalent is not valid for most viewing geometries. Geometries where the ratio is between 0.95 and 1.05 are shown in white. This ratio was calculated using Hapke's equations for directional hemispherical reflectance and bidirectional reflectance.

Disentangling the emitted and reflected components has given rise to a crucial controversy regarding remotely sensed lunar water.

- This task seeks to understand the distribution and nature of organics on the lunar surface using laboratory and remote data. Large areas on the lunar surface have been surveyed using ground-based observations in the 3-4 micron region where organic features due to C-H bonds are observed in some lunar samples, though these are usually attributed to contamination. The data set is being mined to detect organic features. As yet no unequivocal detections have been made, but new observations focusing on the lowest temperatures that may favor organic preservation have been collected and analysis is underway.
- Paul Lucey acquired the first 2-5 micron measurements at new University of Hawaii facility. Data were obtained at ambient and cryogenic temperatures. These measurements show that the instrument is nearly ready to support the data collection proposed in Theme 3. The instrument can measure intimate mixtures of rock powder and ices.

While water is frequently cited as the key lunar resource, other elements including carbon are required for chemical production on the lunar surface, as well as for food production.

1.4 Theme 4: Handling and Curation will develop methodologies for maintaining, storing and handling pristine, sterile samples at cryogenic temperatures

Theme 4 will establish cryogenic sample preservation requirements that will apply to both spacecraft and curatorial facilities, providing guidance for engineers developing lunar sample return spacecraft and hardware.

1.4.1 Julie Mitchell: Co-I, Theme 4 Lead, NASA JSC

- Developed a model of volatile condensation temperatures and a hazard rating system for Shadowed Regions (SRs) and Permanently Shadowed Regions (PSRs) for human surface operations.
- Continued modeling of volatiles reaction products (Dr. Cecilia Amick) and expected distribution of volatiles on the lunar surface (Dr. Julie Mitchell). The calculations and maps produced have been seen by the operations and engineering communities with positive responses. These results are part of a manuscript that is currently in preparation.
- Received several new lab instruments and hardware for conducting laboratory studies of lunar volatile-bearing simulants, including a negative-pressure glovebox, which will provide the initial springboard for creating and handling lunar samples that contain hazardous materials.
- Supported multiple Artemis sampling tools evaluations with astronauts and engineering teams (Fig. 6).

Figure 6. Astronaut Don Pettit performing Artemis sample tools evaluations at JSC. 10/21/20.

2. ICE Five-O Inter-team/International Collaborations

2.1 ICE Five-O and RISE2 (P.I.: T. Glotch)

Both teams have a common interest in measuring space weathering effects with near-field FTIR. Gillis-Davis and Glotch have jointly submitted a NASA Postdoctoral Program announcement related to spectroscopic measurements and spectral modeling of experimentally space weathered lunar analogs, chondritic meteorites and meteorite analog materials.

2.2 ICE Five-O and SEEED (P.I.: C. Pieters)

Members of the two teams (e.g., Gillis-Davis, Pieters, Mustard) are working with Graduate student Chris Kremer on infrared spectra of olivine in the 4-8 μm "cross-over" range as a tool for determining the Mg# of olivine.

2.3 ICE Five-O and IMPACT (P.I.: M. Horanyi)

Gillis-Davis and Horanyi have been collaborating on the ion bombardment of lunar simulants to study the effects of space weathering.

2.4 ICE Five-O and REVEALS (P.I.: T. Orlando)

Both teams are collaborating (Gillis-Davis, Orlando, Jones) on the ion bombardment of lunar simulants to study the effects of space weathering.

2.5 ICE Five-O and LEADER (P.I.: R. Killen)

Prem is a joint Co-I on the LEADER/ICE Five-O teams. Results from ICE Five-O work on isotopic fractionation will inform LEADER models of past, present, and future lunar volatile transport.

2.6 ICE Five-O and CLSE (P.I.: D. Kring)

Stopar is bridging volatile science, exploration, and planning for future polar observations from the surface as a Co-I ICE Five-O team and a CLSE team member.

3. Public Engagement Report

Barb Bruno, Science Activation Lead

- Over the past 8 months Co-I Bruno has built a relationship with Haleakala National Park Rangers.
- In July, Bruno held a three-day workshop, bringing in geologists and cultural practitioners to build science and cultural connection with the park (Fig. 7).
- Supported Haleakala Park staff as they revised their educational programming. Due to COVID, the park visitor center closed and they discontinued their standard interpretation programs (that is, regularly scheduled formal interpretation programs

to large groups of park visitors), as these are no longer allowed under COVID restrictions. They are replacing these with shorter, more informal “pop-up” programs, which they deliver spontaneously to smaller groups (e.g., at trailheads). Since the July training, they have developed 5 pop-up programs, some of which incorporate scientific and/or cultural content learned in the training.

- Expanded online resource repository available to Haleakala park interpreters:

  -https://drive.google.com/drive/folders/1fOhg-xcmR43fDnpQ49sRHQVDiTCZc3rd

- As a result of the July ICE Five-0 training, park interpreters report (1) increased team cohesion and bonding and (2) enhanced appreciation for Hawaiian cultural values. The park interpreters created this poster to express their values:

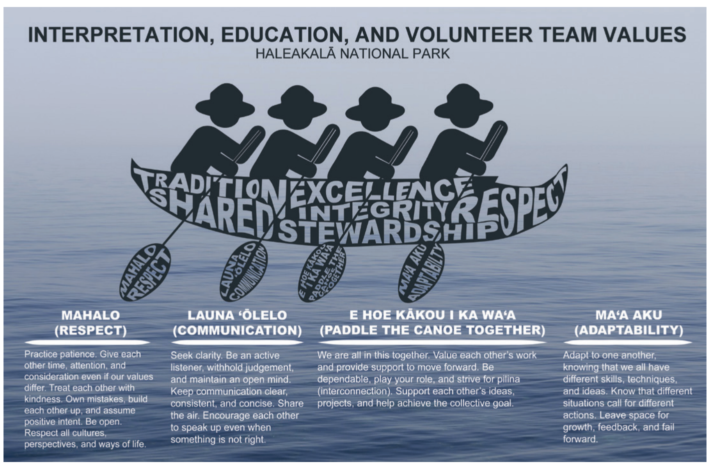


Figure 7: The July training lead by Co-I Bruno included discussions on incorporating Hawaiian values into the ways we live and work. The Haleakala park rangers got together and recast the National Park Service values into a Hawaiian context.

Parvathy Prem has participated in Skype a Scientist (Classroom Conversations with Grade 6-8, AIM Academy, PA; Grade 8, Pacific Crest Middle School, OR; Grade 5, PS 199 Jesse Isidor Straus, NYC), November 2, 6, and 12, 2020.

Julie Mitchell presented to 100+ high school students as part of the Space Exploration and Earth Science (SEES) program hosted by the Texas Space Grant Consortium and the University of Texas at Austin.

Julie Stopar presented for Virtual Programs with NASA Scientists (a libraries program), Fall 2020; Video lecture for Aerospace Corp. aimed at providing mission planners and engineers with technical details about the surface of the Moon and its geology (in production 2019-2020); and presented lunar science and the exploration of the poles as part of a career development program “Summer Science Seminars” for undergraduate interns at the LPI (Aug 2020). Presented at LPI Solar System Exploration Public Engagement Institute event, Feb 2020.

4. Student/Early Career Participation

Undergraduate Students

APL CIRCUIT Undergraduate Interns, Academic Yr 2020–21, effort by Parvathy Prem:

1. Alyse Tran (JHU, Mechanical Engineering)
2. Christopher Alfaro (UMBC, Chemical Engineering)
3. Courtney Carreira (JHU, Physics, Applied Math & Statistics)
4. Katherine-Ann Carr (UMBC, Mechanical Engineering)
5. Oluchi Azubuike (UMBC, Information System)

University of Winnipeg Centre for Terrestrial and Planetary Exploration (C-TAPE), effort by Edward Cloutis:

6. Sahejpal Sidhu (UW, Geography)
7. Nathalie Turenne (UW, Environmental Science)
8. Stephanie Connell (UW, Geography)
9. Alexis Parkinson (UW, Biology)
10. Jesse Kuik (UW, Environmental Science)

Graduate Students

11. Abby Flom, University of Hawaii, Remote Sensing

Postdoctoral Fellows

12. Kenta Ohtaki, University of Hawaii, material science
13. Lionel Vacher, Washington University, meteoritics & cosmology

University of Winnipeg Centre for Terrestrial and Planetary Exploration (C-TAPE), effort by Edward Cloutis:

14. Sandra Potin, University of Grenoble graduate, spectroscopy of planetary materials and minerals; construction of environment chambers and goniometers.
15. Sebastien Manigand, University of Grenoble graduate, Data Scientist.
16. Christy Caudill, University of Western Ontario graduate, lunar and martian analogue missions, spectral data analysis.

5. Mission Involvement

1. Julie Mitchell supported numerous ongoing activities for the Artemis sample return. She continued collaboration and implementation of Artemis science goals with the engineering, spacecraft, operations, and safety communities. Julie also was part of the Artemis Science Definition Team as an ex-officio member.

2. ManitobaSat-1, Ed Cloutis (Collab. Univ. Winnipeg), science payload will carry meteorites and lunar analogs into LEO to see how space weathering affects them by monitoring any color changes. Laser weathering experiments (Theme 1) of meteorite and analog materials will provide a basis for observations and a check to experiments.

3. Volatile & Mineralogy Mapping Orbiter Mission is an ESA funded cubesat. Ed Cloutis, used a three-band lidar (532, 1064, and 1560 nm) to look for ice in permanently-shadowed regions. Measurements of ice/regolith mixtures (Theme 3) will help interpret VMMO results.

4. I-SPI, FROST, and LunaR are three Canadian Space Agency-funded Phase 0 studies that are examining the use of infrared spectroscopy (I-SPI and FROST) or Raman spectroscopy (LunaR) to search for water ice in permanently-shadowed regions. Ed Cloutis (Collab, Univ. Winnipeg) is Science Team Lead for I-SPI and FROST, and P.I. for LunaR.

5. Parvathy Prem participated in LRO as a Mini-RF Co-I, as well as Diviner Science Team Member.

6. Jeffrey Gillis-Davis was a participating scientist on LRO Mini-RF.

7. Julie Stopar participated in LRO as an LROC Co-I. She was also a Co-I on the Intrepid planetary mission concept study for a 4-year lunar rover design to investigate the Moon's volcanic evolution in the heart of the Procellarum KREEP Terrain.

6. Awards

- Brad Jolliff was awarded the SSERVI Shoemaker award.
- Hope Ishii elected as Fellow of Meteoritical Society.
- Julie Stopar received the NASA Planetary Science Division recognition for service and contributions to NASA's Regional Planetary Image Facilities.

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)

Mihaly Horanyi
University of Colorado, Boulder, CO

CAN-3 TEAM

1. IMPACT Team Report

1.1. Dust Accelerator Projects

We have upgraded the calibration of the charge pickup sensors in the accelerator beamline that enable the non-perturbative measurement of the speed of accelerated dust particles. The new calibration techniques provide guidance for future work in general with charge sensitive amplifiers (used across many areas of physics), and the results prompt the need to revisit some of the analysis and interpretation of existing in-situ measurements of dust detectors that were tested and calibrated at our accelerator. For example, the Lunar Dust Experiment (LDEX) orbited the Moon for about 150 days, in the altitude range of 20 km–100 km and characteristic orbital speed of 1.6 km/s. The triggering of the instrument required a dust impact generated charge of 0.3 fC. Based on the updated calibration of the dust accelerator at that time, this threshold impact charge corresponds to a 0.3 μm radius silica particle striking the instrument at 1.6 km/s. The updated calibrations indicate that this threshold particle size has to be revised to a particle radius of about 0.2 μm, representing a 30% reduction in mass (James et al., Rev. Sci. Inst. 91, 113301, 2020, https://doi.org/10.1063/5.0020018).

The dust accelerator facility (Fig.1) remains a unique facility to study hypervelocity (>> 1 km/s) dust impacts for basic physics studies, and for the testing and calibration of flight instruments. We have continued to serve several space missions for dust impact damage studies, testing and calibrating space hardware for NASA's Cassini, New Horizons, Solar Probe Plus, Europa Clipper, IMAP, and ESA's Destiny Plus missions. The facility is open to the US lunar, space and planetary sciences communities, as well as to our international partners.

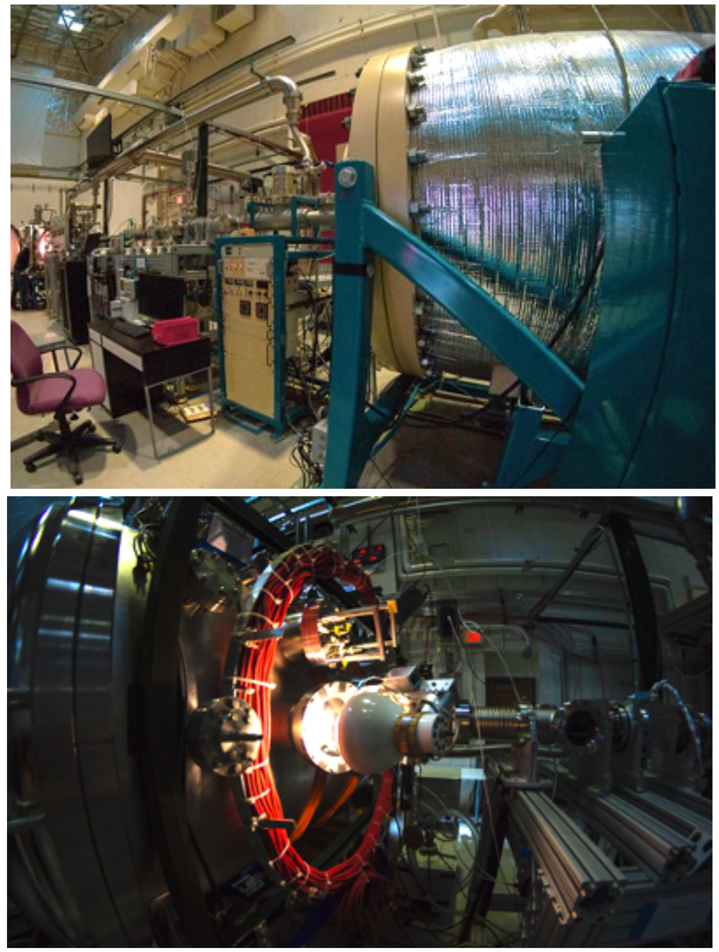


Figure 1. IMPACT continued to upgrade its dust accelerator facility (left) and its various target chambers. Our target options include a) a gas target for meteoroid ablation studies; b) a cryogenic target for ice impact experiments, c) a large impact chamber that can accommodate experiments that need rotational and/or translational staging in the dust beam (right), in addition to specialized single user chambers.

The Laboratory for Atmospheric and Space Physics (LASP) and the Department of Physics completed the construction of a new class 10,000 clean room for IMPACT to support its instrument development efforts for space flight. The IMPACT laboratory received major infrastructure upgrades from the University of Colorado, including: an electrical overhaul of our laboratories; fire sprinkler system installation throughout the entire building, and renovations to build 3 new labs.

1.2. Small-Scale Laboratory Experiments

Electrostatic dust lofting may play an important role in the surface evolution of airless bodies as indicated from a number of unexplained observations, like the lunar horizon glow and dust ponding on asteroids for example. The initial launch velocity of a charged dust particle determines its range of motion; hence it is a critical quantity to assess the dynamics of electrostatic dust transport. IMPACT completed a series of laboratory measurements of the launch velocity of electrostatically lofted dust and its relationship with the dust size (Figs. 2-4). For irregularly shaped dust, similar-sized particles show a large velocity dispersion, indicating a large variation in the inter-particle cohesive force. The maximum launch velocity is shown to decrease with the increase in the dust radius and is on the order of ~0.7 m/s for 15 μm radius particles. The theoretical expectation of an inverse velocity-size relationship of lofted dust has been shown to be consistent with the maximum launch velocity measurements. The dust shape is found to have a significant effect on the lofting process, showing

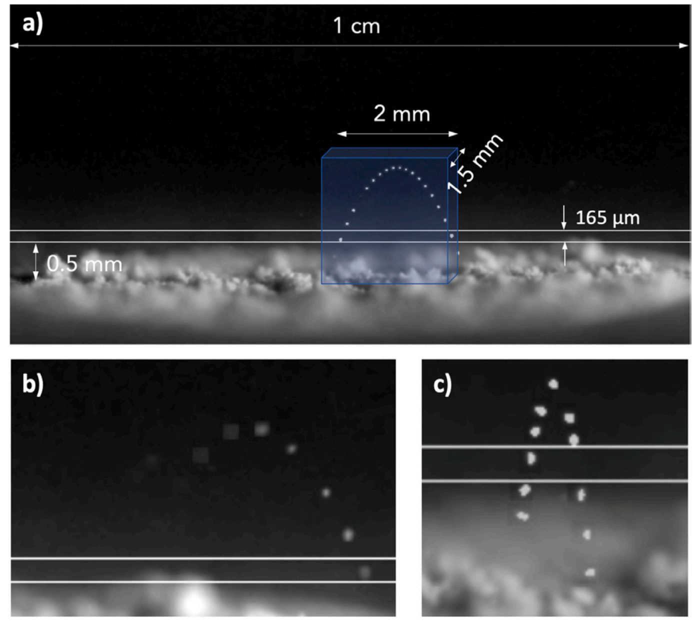


Figure 3. Stacked images showing a dusty surface and trajectories of lofted dust particles. a) Dust particles fill up a crater 1 cm diameter and 2 mm deep. A narrow focal plane normal to the boresight of the camera is in the center of the crater with a depth of ~1.5 mm. Two reference lines are set separated by a small distance ~165 μm and ~0.5 mm above the surface. When a dust particle moves across both lines, its velocity is measured. A blue box (2 mm x 2 mm x 1.5 mm) is illustrated to show the dust selection criterion for analysis. A qualified dust particle needs to travel through the entire box; b) Dust trajectory outside the focal plane; and c) Dust trajectory inside the focal plane, showing particle rotation during the course of flight.

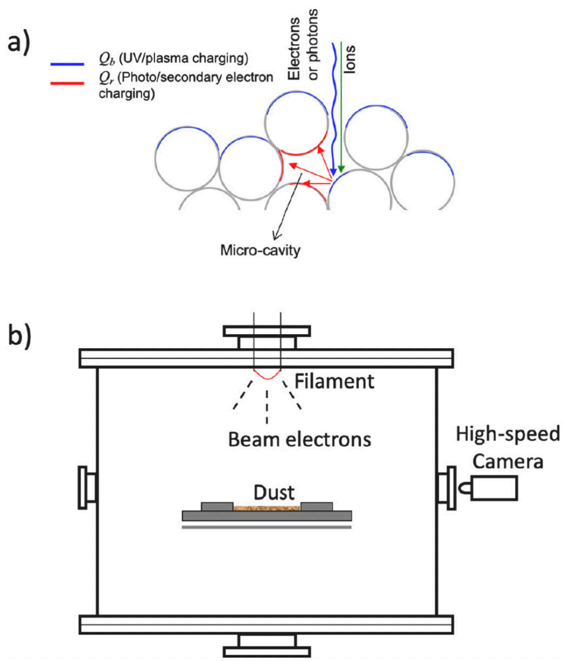


Figure 2. a) The patched charge model for dust particles charging on regolith (Wang et al., 2016a). Inside the microcavity, the blue patch exposed to plasma or UV emits secondary electrons or photoelectrons, which then deposit on the red patches of neighboring particles; b) Schematic of the experimental setup. A 120-eV electron beam is generated using a negatively biased hot filament. Lunar Highlands Type (LHT) simulant particles (<22.5 μm in radius) are exposed to the beam. Lofted dust particles are recorded by a high-speed video camera at 5300 fps and with the resolution of ~11 μm/pixel (see Fig. 3).

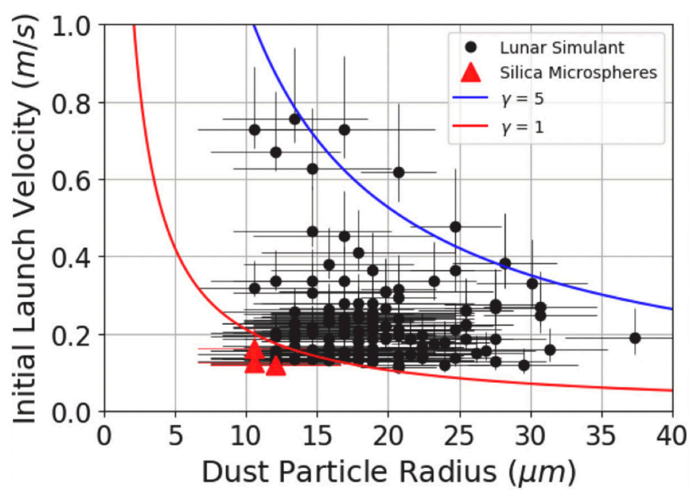


Figure 4. Initial launch velocity as a function of the radius of dust particles for both irregularly shaped LHT simulant (solid circles) and 10 μm radius silica microspheres (solid triangles), respectively. The 20 μm radius silica microspheres remained un-lofted in these experiments. The theoretical curves (solid lines) are shown with γ of 1 and 5, respectively, where the γ factor parametrizes particle shapes. The minimum velocity ~0.1 m/s is limited by the cutoff height in the data analysis.

that irregularly shaped particles are lofted with much larger velocities than spherical particles (Caroll et al., Icarus 352, 113972, 2020, https://doi.org/10.1016/j.icarus.2020.113972).

> These experiments represent a critical step in "Characterizing the surface electric field and the electrostatically transported dust's grain size, charge, and spatial distribution required to provide an understanding of the lunar dust-plasma environment and its impact" (NASA ATREMIS III SDT, 2020).

1.3. Data Analysis

Since the discovery of the Moon's asymmetric ejecta cloud, the origin of its sunward-canted density enhancement has not been well understood. We propose impact ejecta from meteoroids on hyperbolic trajectories (β-meteoroids) that hit the Moon's sunward side could explain this unresolved asymmetry. β-meteoroids are submicron in size, comparable to or smaller than the regolith particles they hit, and can impact the Moon at very high speeds ~100 km/s. Their impact regime may differ from the significantly larger and slower sporadic meteoroids responsible for generating the bulk of the lunar impact ejecta cloud. We compared lunar impact ejecta production to β-meteoroid fluxes observed by multiple spacecraft. If a β-meteoroids are able to liberate similar sized submicron particles, orbital dust detector measurements from LADEE/LDEX only need to detect one ejecta grain out of every 106 β-meteoroid impacts to the lunar surface to explain the sunward asymmetry with this additional population. This finding suggests a β-meteoroids may also contribute to the evolution of other airless surfaces in the inner solar system (Szalay et al., APJ-Letters 890, L11, 2020, https://doi.org/10.3847/2041-8213/ab7195).

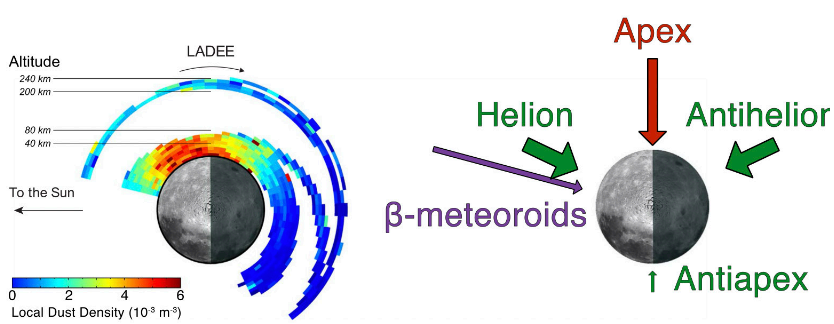


Figure 5. (Left) Lunar ejecta cloud observed by LDEX over the entire LADEE mission. (Right) Impactors in the Moon's equatorial plane. Helion, anti-helion, and anti-apex impactors are all due to impacts from meteoroids on prograde orbits. Apex impactors are from meteoroids on retrograde orbits. γmeteoroids impact the Moon near 11 LT as determined from analytic estimates. The length and width of each arrow qualitatively correspond to the characteristic speed and flux, respectively.

1.4. Modeling

Although they so far appear to be unique to the Moon, swirls have potentially broad implications for both space weathering and planetary magnetism. Possibly the most well-known swirl formation is Reiner Gamma, a tadpole-shaped albedo marking with an overall length of about 70 km, located west of the crater Reiner on the Oceanus Procellarum. The tadpole's head is characterized by an inner bright lobe and two outer bright lobes, set apart by two narrow dark lanes. Reiner Gamma's magnetic topology produces a mini-magnetosphere in which the dark lanes correspond to the areas where the crustal magnetic field is primarily oriented vertically with respect to the surface and the bright lobes are co-located with a more horizontal topology. Earlier results showed qualitative correlations between our numerical plasma simulation results with both optical remote observations of the lunar albedo and in-situ measurements of reflected solar wind. However, the outer bright lobes of the swirl pattern were not well resolved, and the brightness of the inner bright lobes was overestimated. One explanation to these discrepancies could be that these studies focused solely on a scenario where the Reiner Gamma region is exposed to a quiet solar wind impinging on the lunar regolith parallel to the surface normal, while the real lunar albedo pattern must

> The continued analysis of LADEE/LDEX measurements indicate that γmeteoroid impacts can significantly contribute to the generation of the lunar dust exosphere, in addition to the impacts by interplanetary meteoroids of cometary and asteroidal origin.

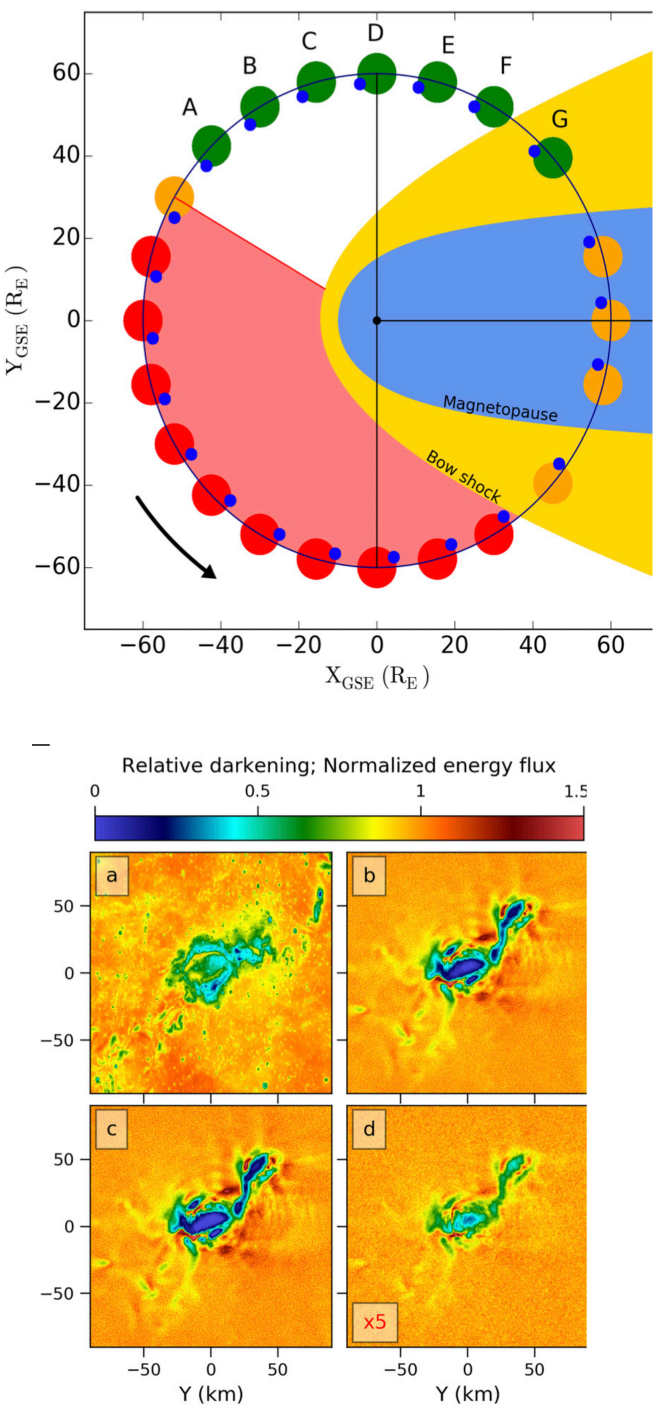


Figure 6. (TOP) The location of the Reiner Gamma region on the lunar surface (indicated with a dark blue dot) during the various phases of the Moon's orbit around the Earth. Segments of the lunar orbit when no or an insignificant amount of particle flux reaches the region are indicated in red and orange, respectively. (BOTTOM) Comparison of the relative darkening (inverse relative brightness) with the simulated energy flux to the surface, integrated over one lunar orbit. (a) Inverse of the LRO-WAC empirically normalized reflectance image. (b–d) Integrated, combined, normalized energy flux profile to the surface combining p+ and He2+, and only p+, and He2+, respectively.

The Reiner Gamma region is an area targeted by one of the next NASA/PRISM landers, making a detailed understanding of the near-surface plasma environment and its response to varying upstream plasma conditions of great interest.

have formed over time and over a wide range of plasma conditions in the lunar orbit (Fig. 6). In order to more accurately estimate the long-term surface effects of the plasma interaction with the magnetic fields co-located with the Reiner Gamma swirl, we integrated the energy flux profiles over the entire lunar orbit, including the solar wind, magnetosheath, tail lobe, and plasma sheet crossings (Deca et al., JGR Planets 125, 2020, https://doi.org/10.1029/2019JE006219).

1.5 Exploration: Dust Hazard Mitigation

Dust mobilized on the lunar surface due to natural processes and/or human activities can readily stick to spacesuits, optical devices, and mechanical components, for example. This may lead to dust hazards that have been considered as one of the technical challenges for future lunar exploration. Several dust mitigation technologies have been investigated over the past years. IMPACT has investigated a new method using an electron beam to shed dust off of surfaces. Recent studies on electrostatic dust lofting have shown that the emission and absorption of secondary electrons or photoelectrons inside microcavities forming between dust particles can cause the buildup of substantial negative charges on the surrounding particles. The subsequent repulsive forces between these particles can cause their release from the surface. Fine-sized lunar simulant particles (JSC-1A, <25 μm in diameter) are used in our experiments. The cleaning performance is tested against the electron beam energy and current density, the surface material, as well as thickness of the initial dust layer. It is shown that the overall cleanliness can reach 75–85% on the timescale of ~100 s with the optimized electron beam parameters (~230 eV and minimum current density between 1.5 and 3 μA/cm2), depending on the thickness of the initial dust layer. The maximum cleanliness is found to be similar between a spacesuit sample and a glass surface. (Farr et al., Acta Astronautica 177, 405-409, 2020, https://doi.org/10.1016/j.actaastro.2020.08.003). Future work will be focused on removal of the last final layer of dust particles and an alternative method using ultraviolet (UV) light (https://www.sciencenews.org/article/electron-beam-space-moon-dust-zap-clean-up).

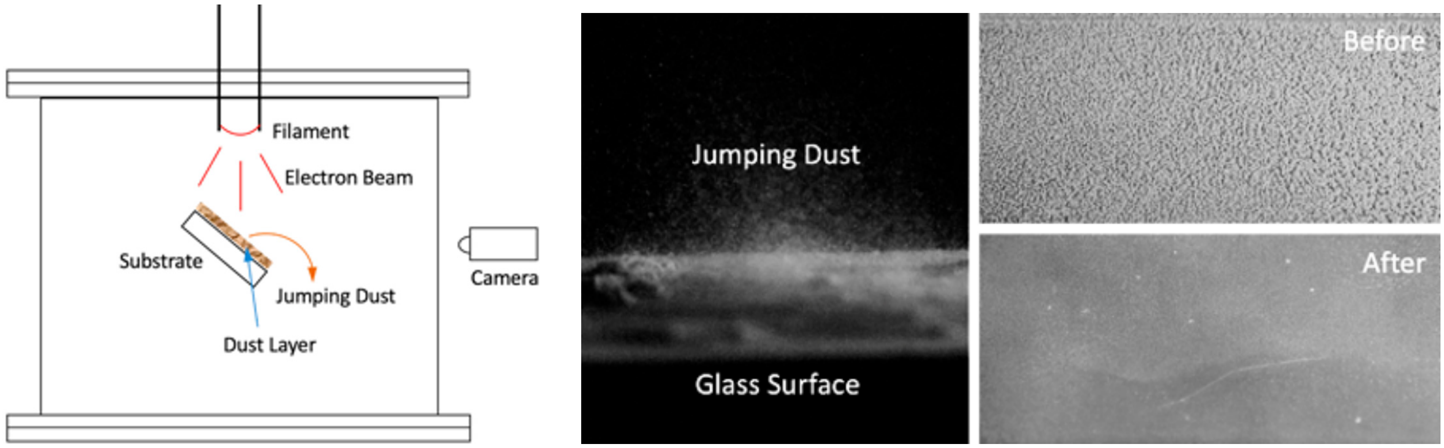


Figure 7. (Left) Schematic of the experimental setup. An electron beam is generated using a negatively biased hot filament. A substrate covered with lunar simulant dust (JSC-1A, < 25 μm in diameter) is set at 45° relative to the horizontal line and exposed to the beam. (Right) Dust jumping off the surface due to exposure to an electron beam (230 eV, 1.5 μA/cm2), recorded by a high-speed video camera at 2000 fps. The changes in the surface cleanliness over time are recorded by a regular-speed video camera.

1.6 Exploration: ISRU

Lunar in-situ resource utilization (ISRU) discussions have recently been focused on the presence and distribution of ice in the upper layers of surface regolith, in particular within the confines of the permanently shadowed regions. Penetrometers provide a robust and straightforward measurement technique for determining soil properties, but previous research fails to reliably show measurement sensitivity to increasing ice content due to difficulties in experimentation at cryogenic conditions. To display the capability of a simple conical penetrometer to discern saturation levels of icy regolith simulant within an expected range, we conducted laboratory penetration and subsequent relaxation measurements of JSC-1A lunar simulant using a new cryogenic apparatus which minimizes sample temperature fluctuation as well as the thermal mismatch between the penetrating probe and tested sample. We measured penetration resistance and force relaxation behavior for JSC-1A lunar simulant under constant displacement rate penetration at ~300 mTorr

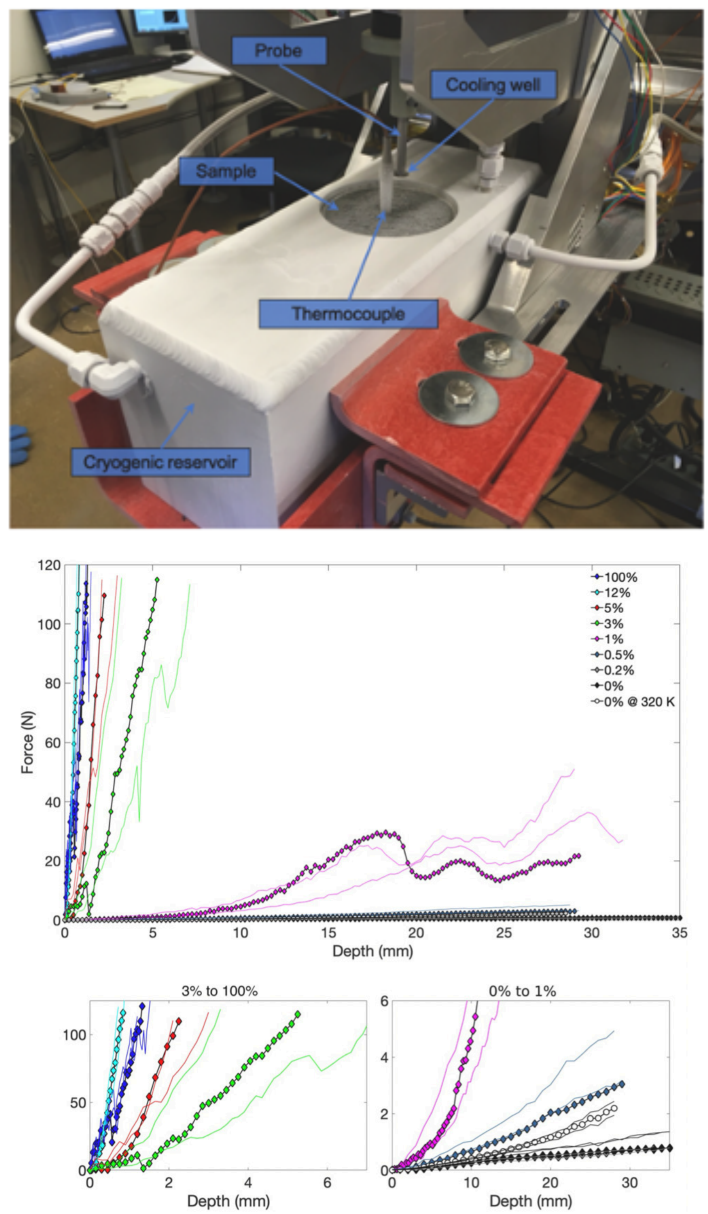


Figure 8. (Top) The cryogenic cooler and penetrometer setup at the Colorado School of Mines. Inlet and outlet hoses provide circulation of liquid nitrogen, as the cooler is hollow to create a cooling, stable reservoir surrounding the sample. The probe itself is seen pressed into the cooling well (at back), while a thermocouple is embedded in the sample center for temperature monitoring during thermal tests. During regular penetration testing, no thermocouple is present in the sample and the entire assembly is sealed within the vacuum chamber. (Bottom) Top: Penetration curves for all ice contents showing resistance force as a function of probe depth, including a test of 0% at 320 K). Tests performed at ~110 K. Markers indicate one of three runs at the same ice content, while solid lines indicate the other two. Bottom: Increased resolution displays for high (left) and low (right) ice content samples.

Extraction ideas - ranging from simple scooping to percussive drilling and thermal (optical) mining using cold-trap volatile capture – require detailed knowledge of the mechanical properties of icy regolith astronauts are likely to encounter. Simple penetrometers can provide a robust and straightforward measurement technique for determining soil properties.

pressure, ~110 K sample temperature, 170 K to 190 K probe temperature, and ice contents of 0% to 12% and 100%. Penetration resistance and relaxation behavior both showed sensitivity to ice content, with parameters of best-fit curve models offering simple empirical predictors of saturation. A critical ice content of 1% to 3%, wherein a significant increase in penetration resistance occurs, is identified as being fundamentally influenced by the filling of substantial pore space with grouting ice. A decrease in viscoelastic behavior of high ice content samples at cryogenic temperatures is noted, and inhibition of relaxation mechanisms due to activation-energy-based temperature effects is also demonstrated in dry, ice-free simulant. Additional research across the spectrum of ice saturations, temperatures, and pressure environments likely to be found in extraterrestrial environments is suggested to improve upon these results, in particular using even more specialized cryogenic systems to reduce thermal issues and increase load capacities and apparatus stiffness. Such additional information will serve to advance the potential use of these results and this technology in future exploratory missions (Atkinson et al., Icarus 346, 113812, 2020, https://doi.org/10.1016/j.icarus.2020.113812)

2. Inter-team/International Collaborations

IMPACT served as the 'center of gravity' for cosmic dust and dusty plasma research within SSERVI, and has complementary research projects with several of the SSERVI teams and international partners.

2.1. Inter-team collaborations

Lunar Environment and Dynamics for Exploration Research (LEADER; P.I. Killen): longstanding successful collaboration on vapor and plasma release due to micro-meteoroid impacts and plasma modeling. Collaboration on the new lunar reference book New Views of the Moon, chapter on "The Dust, Atmosphere, and Plasma at the Moon" by Farrell et al, 2020.

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS; P.I. Orlando): common projects include dust charging, tribo and impact-induced prebiotic chemistry, as well as a jointly mentored NPP Fellow (M.J. Schaible).

Remote, In-Situ, and Synchrotron Studies for Science and Exploration 2 (RISE-2; P.I. Glotch): ongoing projects on understanding the processes related to space weathering by systematically bombarding well-characterized minerals with high-speed dust particles.

Toolbox for Research and Exploration (TREX; P.I. Hendrix): ongoing collaborations on laboratory efforts, IMPACT providing space and technical assistance for the development of a new TREX UV spectroscopy setup.

2.2. International Partnerships

IMPACT has built active relationships with its international partners from Germany, Canada, Norway, and Japan.

Germany: Long-term close collaborations exist between the Cosmic Dust Research Group at the University of Stuttgart, led by Prof. Ralf Srama. We have an active exchange program for students, postdocs and researchers. The University of Colorado and the University of Stuttgart have an active Memorandum of Understanding to set the framework for collaborations in lunar and space research. Theoretical and experimental work on regolith characterization is continuing in collaboration with the dust group at the Technical University, Braunschweig, led by Prof. Jurgen Blum. Impact experiments involving mass spectroscopy are part of an ongoing collaboration with the group at the Free University of Berlin led by Prof. F. Postberg.

Canada: We have common projects with the group at the University of Alberta, led by Prof. R. Marchand on modeling plasma surface interactions.

Norway: Ongoing collaborations with the group at the University of Oslo led by Prof. W. Miloch address new instrument ideas. We have received funding from the Partnership Program with North America, Norway, that pays all travel and living expenses of IMPACT students visiting Oslo, and the Norwegian students visiting us.

Japan: We have been collaborating with the group at the Kobe University led by Prof. Y. Miyake on modeling of plasma-surface interactions to enable a better analysis and interpretation of existing observations and laboratory experiments at IMPACT, and the design of future landed surface experiments to explore the charging, mobilization, and transport of lunar dust.

3. Public Engagement Report

3.1. LunGradCon

(http://impact.colorado.edu/lungradcon/2020/)

IMPACT continued its support of special activities at the request of SSERVI-Central. IMPACT remained the lead organizer for the LunGradCon meeting series since its start in 2010. LunGradCon was organized to enhance the professional development of graduate students and postdocs by providing an opportunity to present and discuss their research in an environment of their peers only and building lasting professional relationships. The meetings are held in conjunction with the NASA Exploration Science Forum. SSERVI-Central provided additional funds to IMPACT to support the participation of the LunGradCon students.

3.2. Classroom Demonstration

IMPACT developed a charge pickup detector for use in classroom demonstrations. The detector can be used in a physics classroom to help high school and introductory-level physics students connect electromagnetic phenomena with measurement techniques that are common to experimental physics and in electronics courses to demonstrate the use of a charge-sensitive amplifier (CSA). Construction of the detector develops students' basic machining and electronics skills, which are crucial in most undergraduate experimental physics opportunities. The detector is designed to nondestructively determine the velocity and charge of the particles (Nerem et al., The Physics Teacher 58, 200, 2020, https://doi.org/10.1119/1.5145417).

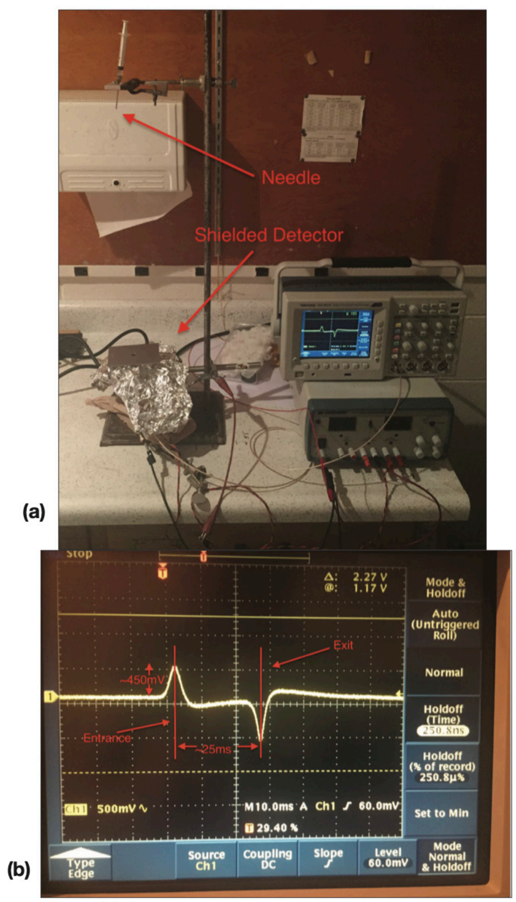


Figure 9 (a) Setup of a charged water droplet experiment.
(b) Oscilloscope trace from charged water droplet. The charge is calculated from the signal amplitude, and the velocity is calculated from the entrance and exit times.

4. Student/Early Career Participation

Undergraduate Students

1. Forrest Barnes
   Control software development
2. Anthony Carroll (graduated 2020)
   Dust dynamics in plasma
3. Erick Diaz
   Dust coater development
4. Alex Doner
   Accelerator experiments
5. Benjamin Farr
   Dust dynamics in plasma
6. Noah Hood (graduated 2020)
   Dust dynamics in plasma
7. Thomas Keaton (graduated 2020)
   Dust dynamics in plasma
8. Zuni Levin
   SIMION studies
9. Liam Merz-Hoffmeister (graduated 2020)
   Impact charge measurements
10. Destry Monk (graduated 2020)
    Accelerator control systems
11. Michael Nothem (graduated 2020)
    Dust accelerator support
12. Michael Voss
    Dust accelerator support

Graduate Students

13. Jared Atkinson (CO School of Mines)
    ISRU Experiments
14. Edwin Bernardoni
    Plasma theory
15. Michael DeLuca (graduated 2020)
    Micrometeoroid ablation experiments

Postdoc at Princeton University

16. Alessandro Garzelli
    Impact ejecta detection

17. Samuel Kočiščák (Charles University, Prague)
Impact experiments on s/c antennas

18. Marcus Piquette (graduated 2020)
Surface/plasma interaction modeling

Research Associate at LASP

19. Joseph Samaniego (graduated 2020)
Langmuir probe measurements

NSF Research fellow in Antarctica

20. Mitchell Shen
Impact experiments on s/c antennas

21. Zach Ulibarri
Ice target experiments

22. LiHsia Yeo
Solar wind experiments

23. William Goode
Accelerator experiments

New Faculty Members

24. Jordy Bouwman
Cosmochemistry

6. Mission Involvement

1. NASA New Horizons, Student Dust Counter, P.I.: M. Horanyi, IMPACT dust accelerator experiments are being used to extend the calibration data base of this instrument for oblique dust impacts (M. Piquette et al., Calibration of Polyvinylidene Fluoride based dust detectors in response to varying grain density and incidence angle, Rev. Scientific Instruments 91, 023307, 2020, https://doi.org/10.1063/1.5125448).

2. NASA PICASSO program supports the technology development of the Double Hemispherical Probe (DHP) instrument, P.I.: X. Wang. The initial laboratory demonstration of the DHP was supported by SSERVI. DHP is designed to improve space-based plasma density and temperature measurements, especially in flowing plasmas, regions with UV illumination, and to minimize the effects of spacecraft charging on the analysis and interpretation of the data (J. Samaniego et al., JGR-Space 125, article id. e28508, 2020, 10.1029/2020JA028508).

3. NASA DALI program supports the development of the Electrostatic Lunar Dust Analyzer (ELDA) instrument, P.I.: X. Wang. ELDA was initially designed based on SSERVI supported laboratory experiments. An updated version (EDA) is part of a PRISM 2021 payload proposal. EDA would measure the properties (mass, charge, speed) of electrostatically mobilized and transported dust on the lunar surface.

4. Europa Clipper, Surface Dust Analyzer (SUDA), P.I.: Sascha Kempf. This impact plasma ionization time-of-flight dust instrument has been initiated by SSERVI funded accelerator experiments. SUDA will provide a compositional surface map of Jupiter's moon Europa, by analyzing the makeup of ejecta particles generated from its surface by the continual impacts of interplanetary micrometeoroids.

5. NASA Interstellar Mapping and acceleration Probe (IMAP), Interstellar Dust Experiment (IDEX), P.I.: M. Horanyi. IDEX will measure the composition of interplanetary and interstellar dust. Similar to SUDA, this instrument development was enabled by SSERVI-supported initial experiments at our dust accelerator facility.

IMPACT's initial motivation for developing impact plasma ionization time-of-flight composition analyzers was to extend the capabilities of the Lunar Dust Experiment (LDEX) flown on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission in 2013-2014. LDEX itself was originally developed by SSERVI's predecessor, the NASA Lunar Science Institute (NLSI). LDEX discovered a permanently present dust exosphere engulfing the Moon, sustained through the continual bombardment by interplanetary dust particles. Incoming particles also generate ejecta from permanently shadowed regions, and a SUDA/IDEX type instrument could be used to explore the makeup of their volatile content from a polar orbiting spacecraft and assess the accessibility of their volatile content for future ISRU needs.

Lunar Environment And Dynamics for Exploration Research (LEADER)

Rosemary Killen

NASA Goddard Space Flight Center, Greenbelt, MD

CAN-3 TEAM

1. LEADER Team Report

1.1. LEADER Theme 1: Environmental Connection to Volatiles

LEADER Co-Is are modeling the past, present and future of lunar volatiles: from ancient volcanic atmospheres, to the contemporary sodium exosphere, to future spacecraft-generated exospheres. Co-I O. J. Tucker led an investigation into the effect of magnetospheric shielding on solar wind interactions with the lunar surface and exosphere. Tucker et al. (2020a) predict that measurements of the OH surface concentration at low latitudes on the night side and of the degassed H_2 exosphere while in Earth's magnetotail could elucidate the role of the solar wind in the lunar hydrogen cycle. Meanwhile, Co-I Jason McLain investigated hydrogen implantation and OH production through laboratory experiments, in which samples of fused silica and lunar regolith were irradiated by a 2 keV H_2+ beam. Co-Is Dana Hurley and Bill Farrell were part of a team who discovered a 6 µm signature of molecular water on the sunlit lunar surface (Honniball et al., 2020), while Co-Is Dana Hurley and Andrew Poppe contributed their expertise as co-authors on a paper by Li et al. (2020) on the unexpected detection of hematite at lunar high-latitudes. Co-I Prem made major contributions to the report by the National Academies Committee on Planetary Protection: Planetary Protection for the Study of Lunar Volatiles (2020).

This year, LEADER Co-Is continued to investigate the lunar environmental connection to volatiles through space and time: from water at the lunar surface to sodium in the upper exosphere, and from ancient volcanic atmospheres to future spacecraft-generated exospheres.

P.I. Rosemary Killen and colleagues continued their observations of the lunar sodium corona with the Goddard Lunar Coronagraph located at the Winer Observatory in Sonoita, Arizona. Complementing these long-term, ground-based observations, Co-I Menelaos Sarantos and colleagues analyzed LADEE data to characterize variations in exospheric sodium with local time as observed from orbit. Highlights of this work include the discovery of a correlation between high exospheric column density and increased ion flux to the lunar surface (Killen et al., 2021) and variations in exospheric structure that may be due to inhomogeneities in the distribution of sodium on the lunar surface (Sarantos et al., under review).

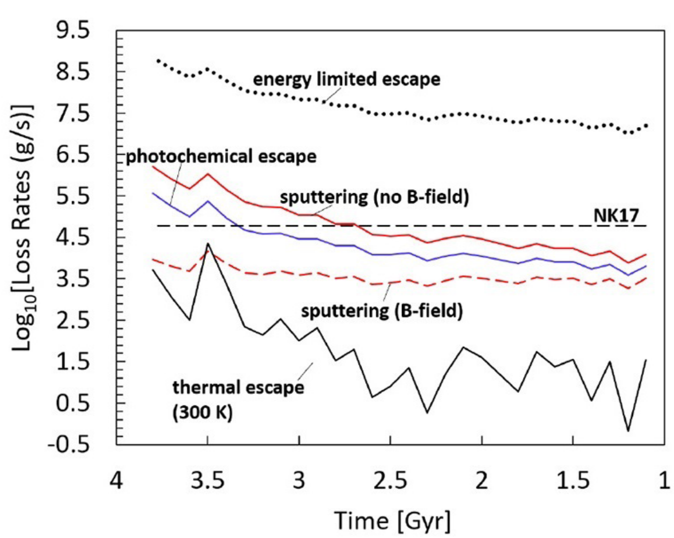


Figure 1. Tucker et al. (2021) calculated loss rates of an early CO-dominated volcanically-generated transient atmosphere. This figure compares the previously assumed loss rate (Needham & Kring) to updated loss rates driven by thermal processes (Jeans escape and energy limited escape) and non-thermal processes (photochemical escape and sputtering, with/without a paleo-magnetic field). Loss rates vary significantly over time due to variations in volcanic outgassing. Estimated lifetimes of transient atmospheres range from ~1000 years to ~1 My.

LEADER

There has been renewed interest recently in the possibility that the Moon may once have had a volcanically-generated atmosphere. Co-I O.J. Tucker led work that, for the first time, considered in detail the physical mechanisms that may have led to the loss of such an atmosphere (Tucker et al., 2021). In related work, Co-I Hurley modeled the exospheric transport of CO_2 to polar cold traps. Initial results indicate that the amount of CO_2 released by a 500 m radius comet or a pyroclastic eruption volume of 75 km3 could supply a 1 mm thick layer of CO_2 to sub-55 K cold traps (Hurley et al., 2019).

Looking ahead to future studies of the lunar exosphere from the Moon's surface, Co-I Parvathy Prem led an investigation into the fate of spacecraft exhaust gases released during a nominal lunar landing. Prem et al. (2020) found that exhaust water vapor may persist in the lunar environment for longer than two lunar days, presenting both an important opportunity to study volatile interactions with the lunar regolith in-situ, as well as a need to account for exhaust gases in measurements of surface and exospheric volatiles. LEADER Co-Is continue to model the transport of spacecraft exhaust volatiles to understand the environmental impact of lunar landings and to support CLPS instrument science objectives.

1.2. LEADER Theme 2: Dust Tribocharging and Chemistry

Several members of the Dust-Tribocharging & Chemistry theme (Drs. Elsila-Cook, McLain and Schaible) experienced a significant delay in their work due to restrictions on experimental work due to the COVID pandemic. Fortunately, these investigations have been able to restart now that restrictions are easing. Dr. McLain has been building a new experimental setup to study space weathering of lunar soils. This LEADER experiment is nearing completion and will enable in-situ/in-vacuo reflectance infrared spectra during/after proton irradiation of a suite of Apollo era soils. Dr. McLain monitors IR reflectance spectra of the lunar soils, particularly hydroxyl radical formation, to determine conversion rates and hydroxyl stability. Dr. McLain and Dr. Elsila-Cook will also use this new experimental apparatus to deposit in-vacuo organic and prebiotic molecules on proton irradiated lunar soils. The polymerization or degradation of these organic molecules will be measured in Dr. Elsila-Cook lab at GSFC using chromatographic separation of soil extracts coupled with mass spectrometry.

> Dust Theme members are developing experimental, computational, and analytical models to understand the chemistry of space weathering, the effect of dust on biological materials, and the electrical interactions of regolith grains.

Dr. Schaible is a SSERVI NASA postdoc fellow at GATech working with both LEADER and REVEALS to study dust grain electrification and reactivity. Dr. Schaible has designed a new technique to reliably deposit electrostatically charged lunar dust analogs onto biomolecular films. This new technique will be used to analyze both biofilm damage and dust grain passivation. A Faraday tube assembly is under development to passively measure the extent of electrostatic dust grain charging. Dr. Schaible is also designing a mechanism to insert and remove the biofilms from the grain interaction region to send to the GSFC Analytical Astrobiology Lab (Dr. Elisa-Cook) in order to measure the chemical reactivity potential of the electrified dust grains.

Dr. Hartzell's investigation of triboelectric charging of regolith has both experimental and computational components. This investigation will inform future efforts to model the tribocharging induced by exploration vehicles. Given the restrictions on experimental work, the focus this year was on computationally modeling the exchange of charge between regolith grains in LIGGGHTS, an open source Discrete Element Method simulation that models the interactions of hundreds of thousands of grains. The goal is to replicate Dr. Hartzell's tribocharging experiment test-stand in LIGGGHTS to enable validation of the tribocharging model and LIGGGHTS implementation. A post-processing charge transfer method has been implemented and Dr. Hartzell and her student are in the process of testing different charge exchange models to attempt to match the experimental results. Figure 2 shows

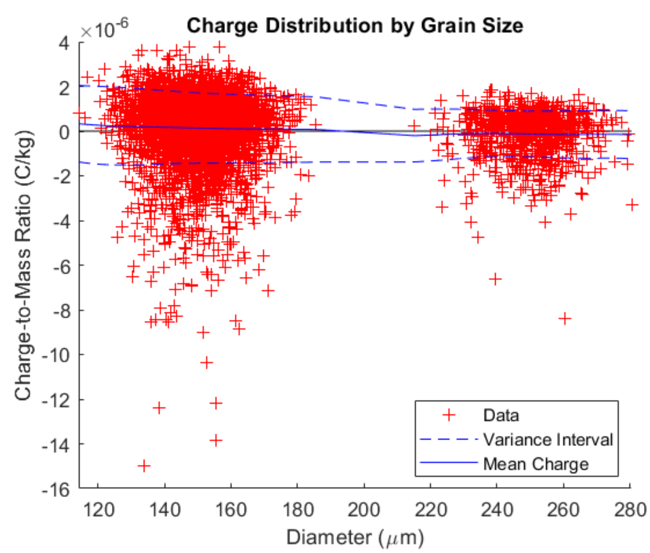


Figure 2. Example charge distribution generated using a triboelectric charge exchange model implemented (via post-processing) with LIGGGHTS.

the type of output generated from the computational and experimental models.

Dr. Marshall has been investigating the relationship between adhesion and aeolian dust mobilization. Conventional threshold models for aeolian transport of dust & powders assume an adhesion component between grains that enhances bulk cohesiveness and results in higher wind thresholds as grain size diminishes. This had led to a general belief that dust on Mars should be difficult to lift. Yet the evidence suggests otherwise–dust is regularly mobilized at very moderate wind speeds. It is proposed that adhesive forces are actually making thresholds easier rather than more difficult. This occurs by the production of high porosity microscopic structures during dust deposition with adhesion forces accommodating the structural vacancies. Dr. Marshall's work suggests that conventional aeolian threshold curves provide no 'dust compressibility' factor and therefore erroneously predict high thresholds for particulates smaller than about 70 microns. These results impact our understanding of dust entrainment by aerodynamic, electrostatic, and gravitational/centrifugal forces on Earth, Mars, Titan, asteroids, and other Solar System bodies.

1.3. LEADER Theme 3: Plasma-Surface-Object Interactions

The LEADER plasma team continued its successful campaign to understand lunar plasma-surface-object interactions. The LEADER team focuses on answering the question: "How does plasma interact with the lunar surface, its tenuous atmosphere, and exploration systems for past, present, and future conditions?"

> The Plasma Theme uses models and validating data sets to derive the plasma environment at our Moon and at Phobos in the solar wind and in planetary geomagnetic tails. The lunar models are used to determine the charging and discharging of human systems for exploration activities.

The LEADER plasma team conducted fundamental data analysis and theoretical investigations primarily focused on moons and their interaction with the surrounding plasma environment. Beyond the terrestrial system, LEADER members investigated the multi-faceted plasma-surface interactions at Phobos, finding a complex pattern of weathering by solar wind and Martian ions on the moon's surface [Nénon et al., 2019, 2021].

A number of LEADER analyses of observations from Earth's Moon focused on the complex interaction of the Moon with the Earth's magnetospheric environment, a fundamentally different physical interaction than that of the Moon with the solar wind. LEADER studies found that lunar ions can be accelerated by magnetic forces in the magnetotail lobes [Cao et al., 2020a], and that the resulting accelerated ions can be used as a tracer of magnetospheric convection [Cao et al., 2020b]. These effects also perturb the local environment in a number of other ways, resulting in observable perturbations to the magnetotail plasma around the Moon [Kistler et al., submitted]. The outflow of ions from the terrestrial environment into the magnetotail may also affect the lunar surface and its chemical nature [Li et al., 2020].

Meanwhile, in the terrestrial magnetosheath, the lunar wake can be severely distorted and affected by upstream space weather influences [Rasca et al., 2021].

Other Moon-focused LEADER studies looked at fundamental physical processes, including the interactions between the ambient solar wind plasma and the small-scale lunar magnetic fields [Chu et al., submitted; Deca et al., 2020], and the structure of the lunar wake near polar craters [Rhodes et al., 2020a,b]. The latter case has implications for exploration, given the very low-density plasma present in polar craters, and LEADER team members conducted detailed investigations of the implications for tribocharging of exploration systems (see Fig. 3) [Rhodes et al., 2020c].

Indeed, LEADER continues to explore the synergy between science and exploration. LEADER team members have been actively engaged in exploration planning,

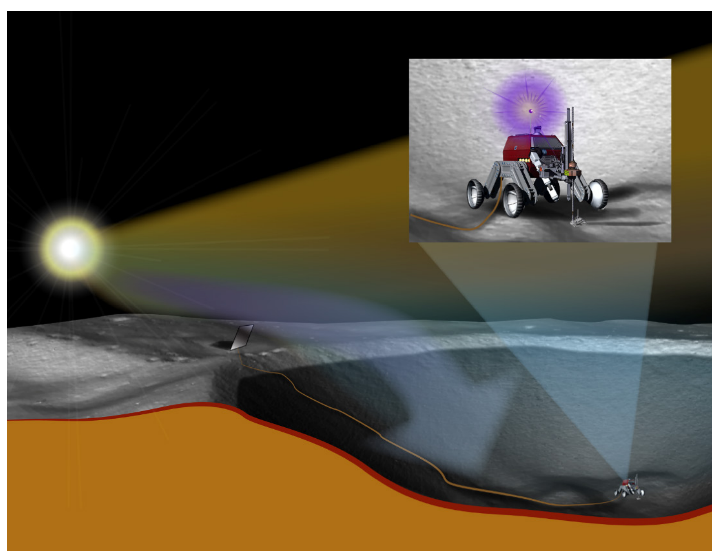


Figure 3. Schematic illustration of plasma flow over a lunar polar crater, and its effects on exploration systems.

providing inputs to JSC exploration teams and to MSFC's development of environmental specifications in support of the Artemis human exploration program.

1.4. LEADER Theme 4: Interaction with the Space Radiation Environment

The Moon is exposed to two primary types of space radiation: galactic cosmic rays (GCRs) and solar energetic particles (SEPs). SEPs can alter lunar soil through a process called dielectric breakdown ("sparking"), and both GCRs and SEPs can affect the radiation exposure of astronauts on or near the Moon. LEADER has made important strides in understanding both aspects of how radiation affects the Moon and its environment.

1.4.1. Evidence for dielectric breakdown weathering on the Moon

Co-I Andrew Jordan has found the first observational evidence suggesting that solar energetic particles cause dielectric breakdown, or "sparking," in cold soil on the Moon [Jordan, 2021]. He has shown that a combination of meteoroid impacts and dielectric breakdown ("sparking") can explain how the reflectance of the lunar maria varies with latitude. This implies that the solar wind plays at most a minor role in space weathering, and it may explain why lunar swirls are brighter and more immature than their surroundings. This work lays the foundation for future experimental and data analysis that the LEADER team will perform, and it will help our understanding of space weathering on other airless bodies that are exposed to high fluxes of energetic charged particles [e.g., Jordan, submitted to Icarus].

1.4.2. Predicting the next solar cycle

Co-I Fatemeh Rahmanifard has led work showing that the Sun is moving into a new period of persistently low solar activity—a secular solar minimum [Rahmanifard et al., 2020]. Consequently, galactic cosmic ray radiation doses will likely be even higher than already unprecedented levels seen during the previous solar cycle, limiting deep space missions for astronauts to 290 days (45-year old male astronauts) and 204 days (female). She is building on this work to create a product that can predict future solar cycles [Rahmanifard et al., in preparation].

LEADER has shown that the Sun is moving into a new period of persistently low solar activity. This affects predictions for the permissible mission duration for astronauts at or near the Moon.

In addition, Co-I Jody Wilson is leading work to predict the maximum number of sunspots in the next solar cycle (cycle 25) via patterns in sunspot number. This method is highly accurate in predicting the subsequent cycle from the one preceding, improving on previous studies [Wilson et al., 2020, AGU abstract]. These two approaches led by Rahmanifard and Wilson will enable LEADER to develop robust predictions of the radiation environment and the resulting permissible mission duration on or near the Moon during the next solar cycle.

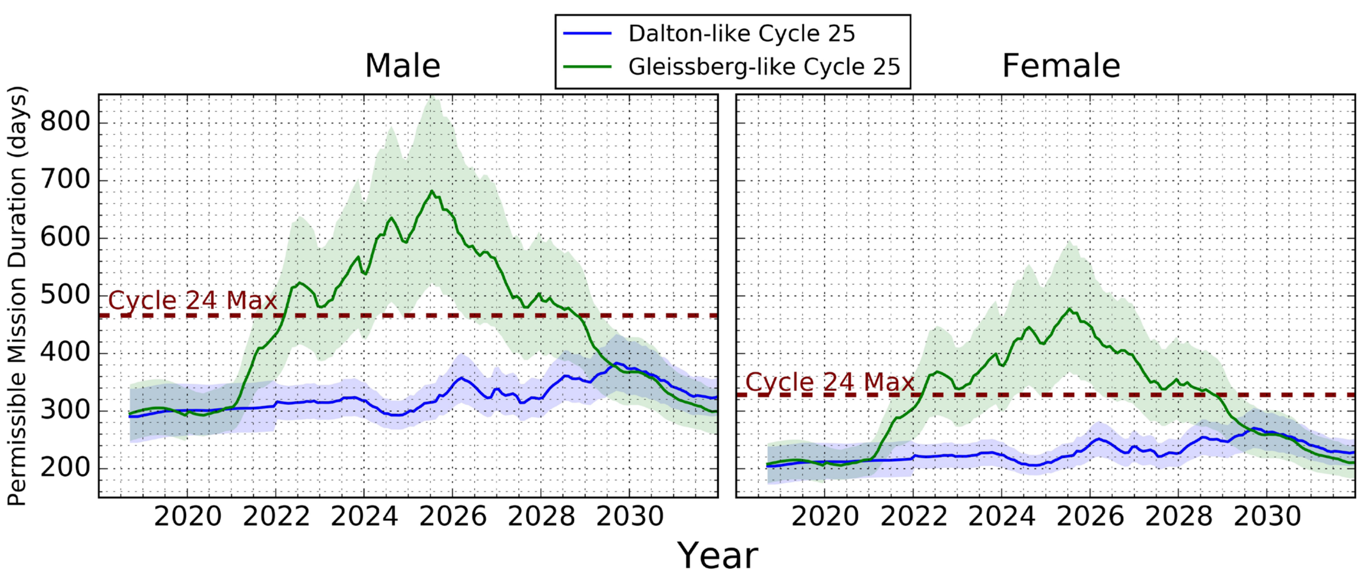


Figure 4. Permissible mission duration for two possible scenarios in the next solar cycle: either a Dalton- or Gleissberg-like cycle. Left: 45-year-old male astronaut. Right: 45-year-old female astronaut. Dashed maroon line shows permissible mission duration for male (female) astronauts at the maximum of solar cycle 24 (Figure from Rahmanifard et al. [2020]).

1.5. Other LEADER Science Activities

1.5.1. Artemis EVA and HLS support

LEADER team members Kelsey Young, Bill Farrell, Andrew Poppe, and Jasper Halekas have been actively engaged in JSC exploration teams and in MSFC's development of environmental specifications in support of the Artemis human exploration program. LEADER Co-I Young has been the GSFC-JSC liaison directing JSC engineering teams to GSFC science personnel who can support the EVA and Human Landing System (HLS) efforts. She has organized internal GSFC efforts and transmits ongoing study results (including our LEADER results) to GSFC management. More tactically, LEADER team members have contributed to the Design Specifications for the Natural Environment (DSNE) including description of the lunar plasma environment expected at the surface and at Gateway orbits. Former DREAM2 post-doc Heidi Haviland is now a civil service scientist at MSFC who assisted in the organization of these DSNE input and reached out to the LEADER team members for the added support. Engineering teams at JSC are creating space suit requirements and are examining expected electrical potentials associated with photoemission, plasma charging and boot-regolith tribocharging. LEADER team member Farrell has given 2 presentations to the group on this subject and is involved in discussions with these engineers. JSC engineers are also involved in dust adhesion and tribocharging analysis and LEADER team member have been asked to provide input to these endeavors.

1.5.2. Decadal Survey involvement

LEADER Co-I's were authors on seven decadal white papers. Prem, Hurley and Farrell each led one; we were co-authors on papers led by Lucey, Richey, Tavares, and Watkins. Hurley, Prem and Farrell presented to the Decadal Mercury and Moon panel. Farrell is sitting on the Mercury and Moon Decadal panel.

1.5.3. CLPS program involvement

LEADER work is being used to define objectives and requirements for the CLPS mass spectrometer (PITMS and SEAL) and Radio/Plasma wave (ROLSES).

2. Inter-team/International Collaborations

2.1. Inter-team Collaborations

LEADER team members are in continual contact and collaboration with other SSERVI teams, science mission teams, and exploration architecture teams. Examples of LEADER interactions with other SSERVI teams include:

REVEALS: LEADER's Farrell is part of the REVEALS Science Advisory Board and the team works together on modeling and lab efforts regarding solar wind implantation and surface hydroxylation at the Moon and other airless bodies. The two teams share NASA Post-doc Micah Schaible, funded via SSERVI-Central NPP award to perform lab work on the biochemistry and electrical passivity of irradiated surfaces.

NESS: LEADER and NESS share collaborators in understanding and assessing the space environmental effects on a sophisticated and sensitive radio astronomy system. We currently supported NESS colleagues on assessing the lunar dust and electrostatic environment, and how to better-ground the radio system.

TREX: LEADER team members Hurley and Farrell are working with TREX P.I. Hendrix on the UV signature of surface water at the Moon. REVEALS team members are also involved. O.J Tucker has been collaborating with Lynnae Quick of SSERVI's TREX team, considering the conditions of the lava outcrops leading to an early Moon atmosphere.

RISE2: LEADER team members are collaborators on irradiated grain reactive chemistry that feeds into Rise4's grain cell survivability work.

IMPACT: LEADER maintains strong cross-team collaboration including post-doc opportunities for students, like A. Poppe who did his thesis work under CCLDAS and is now a key LEADER team member. LEADER modelers (Poppe, Zimmerman) are working with IMPACT team members (Daca, Wang) on magnetic anomaly and grain-grain surface charging studies.

2.2. International Partners

Sweden: LEADER team members continue close interactions with investigators at the Swedish Institute of Space Physics in Kiruna Sweden. LEADER Collaborator Shahab Fatemi relocated from UCB to Kiruna and is working closely with LEADER's NPP Anthony Rasca in modeling the plasma flow about the Moon in the geomagnetic tail.

3. Public Engagement

The LEADER team responded to this year's changing constraints by focusing on digital public engagement efforts. Team members visited virtual classrooms and lecture halls, contributed to social media posts and articles sharing their work, joined large-scale online STEM engagement events, and more.

3.1. Support for Digital Events

LEADER team members took active roles in online community events in 2020. Tucker participated in #BlackInGeoScienceWeek on Twitter, contributing to a Q&A session as well as a panel discussion entitled "Making an Impact in Planetary Science." Prem served as a mentor-judge at the SACNAS (Society for Advancement of Chicanos/Hispanics and Native Americans in Science) Conference, meeting one-on-one with students to discuss their research and career goals. Misra reviewed virtual posters and oral talks as a judge for the Outstanding Student Paper award at the AGU 2002 Fall Meeting. LEADER also supported International Observe the Moon Night, an annual, worldwide public engagement initiative which was estimated to have reached an unprecedented 500,000 participants this year. Barry began serving on this event's coordinating committee in April 2020 and answered questions from the public as part of the #ObserveTheMoon #AskNASA session during the event itself.

Additional LEADER team contributions to virtual events included Nenon's recorded talk about the Martian atmosphere's leakage to Phobos for AGU's Science Theater (available for public viewing at https://bit.ly/37XtM2E), Tucker's leadership of Moon and Mercury session planning for the Division of Planetary Science (DPS) Meeting, and Tucker's presentations on the lifetime of the early Moon atmosphere at both the National Society of Black Physicists Meeting and the NASA Exploration Science Forum.

3.2. Online Content Creation

Recent research led by Rahmanifard and Prem caught the attention of science writers who, with Rahmanifard and Prem's help, promoted their work to broad audiences. Rahmanifard's study examining the current solar cycle and its possible effects on cosmic radiation was featured in a Space Weather Archive article (https://bit.ly/3rFRCrF). Prem's simulation of lunar lander exhaust gases appeared in releases from JHU/APL and NASA (https://bit.ly/3pCXv79, https://go.nasa.gov/39UN1ex). Prem and Barry collaborated to compose a series of social media posts highlighting Prem's research for NASA's Moon and Artemis Twitter accounts (Figure 5).

3.3. Virtual Visits and Other Activities

Several classrooms received visits from LEADER scientists in 2020. Prem participated in the 'Skype a Scientist' program, connecting with AIM Academy in Pennsylvania, Pacific Crest Middle School in Oregon, and PS 199 Jesse Isidor Straus in New York City. Tucker joined classes at Boys of Latin Philadelphia Charter School to discuss

water on the Moon. For other audiences, Halekas and Killen presented comprehensive lectures on plasmas and exospheres, respectively, to the Taiwan Mini-Moon Series (https://bit.ly/35kfjfg), Tucker gave an invited seminar for New York University Abu Dhabi's Space Weather Series, Barry shared information about LEADER's work as part of a presentation to the National Science Teaching Association's Aerospace Advisory Board, and Prem gave an interview in Malayalam with the Dubai-based radio station Hit 96.7 FM.

4. Student/Early Career Participation

Undergraduate Students

1. Michael Kistler: University of Iowa, Plasma Team, graduated, pursuing a career in education.
2. Lexi Leali: University of Iowa, Plasma Team.
3. Giovanni Bacon: Embry Riddle Aeronautical University intern at GSFC with Killen, Volatiles Team.
4. Irima Ajang: Howard University intern at GSFC with Killen, Volatiles Team (pursuing a medical degree).
5. Elijah Catalan: Howard University Intern at GSFC with O. J. Tucker, Volatiles Team. Presently a PhD student in UCLA's Institute of Environment and Sustainability, has gotten into field and lab research.

6. Ajani Smith-Washington: Howard University intern at GSFC with Menelaos Sarantos and Rosemary Killen, Volatiles Team. Presently applying for graduate school.

Graduate Students

7. Jennifer Bates: University of Maryland, working with Christine Hartzell on dust.

Postdoctoral Fellows

8. Feng Chu: University of Iowa (now moved to Los Alamos National Lab), plasma.

9. Xin Cao: University of Iowa, plasma.

10. Dylan Carter: University of Maryland, dust (has now secured a permanent position as a contractor for the Air Force at Edwards AFB near Rosamond, CA).

11. Quentin Nenon: University of California Berkeley, plasma (has an additional two years).

12. Parvathy Prem: JHU/APL (now in a permanent position at APL), volatiles.

New Faculty Members

13. Fatemeh Rahmanifard: University of New Hampshire, radiation.

14. Wouter de Wet: University of New Hampshire, radiation.

15. Christine Hartzell: University of Maryland, dust: obtained tenure.

5. Mission Involvement

5.1. P.I., Co-I, and Guest Investigator roles

Shown below are LEADER team member roles on current and planned missions. (PSD= NASA's Planetary Science Division, HSD= NASA's Heliophysics Science Division, AES=NASA's Advanced Exploration Systems Division).

1. PSD/CLPS/Collier/Co-I and Instrument Lead LEXI
2. PSD/CLPS/Colaprete/P.I. of NIRVSS
3. PSD/CLPS/Hurley/Co-I on SEAL
4. PSD/CLPS/Prem/TM on SEAL
5. PSD/CLPS/Elphic/P.I. of NSS
6. PSD/CLPS/Stubbs/Co-I on MAG
7. PSD/CLPS/Bale*/P.I. on LuSEE
8. PSD/CLPS/Poppe/Co-I on LuSEE
9. PSD/CLPS/Halekas/Co-I on LuSEE
10. PSD/CLPS/MacDowall*/P.I. of ROLSES, Co-I on LuSEE
11. PSD/CLPS/Farrell/Co-I on ROLSES, PITMS, SEAL, MAG
12. PSD/Lunar Reconnaissance Orbiter/ Keller/Deputy Project Scientist
13. PSD/Lunar Reconnaissance Orbiter/Schwadron/ CRaTER P.I.
14. PSD/Lunar Reconnaissance Orbiter/Spence/ CRaTER Co-I and former P.I.
15. PSD/ Lunar Reconnaissance Orbiter/Jordan/CRaTER Co-I
16. PSD/ Lunar Reconnaissance Orbiter/Wilson/CRaTER Co-I
17. PSD/ Lunar Reconnaissance Orbiter/deWet/CRaTER Co-I
18. PSD/ Lunar Reconnaissance Orbiter/Rahmanifard/ CRaTER Co-I
19. PSD/ Lunar Reconnaissance Orbiter/Stubbs/ CRaTER Co-I
20. PSD/ Lunar Reconnaissance Orbiter/Stubbs/LAMP Co-I
21. PSD/Lunar Reconnaissance Orbiter/Hurley/LAMP Co-I
22. PSD/Lunar Reconnaissance Orbiter/Stubbs/ Participating Scientist
23. PSD/Lunar Reconnaissance Orbiter/Prem/MiniRF/ TM
24. PSD/LADEE/Elphic/Project Scientist
25. PSD/LADEE/Delory/Deputy Project Scientist
26. PSD/LADEE/Colaprete/UVS P.I.
27. PSD/LADEE/Hodges/NMS Co-I
28. PSD/LADEE/Stubbs/Guest Investigator
29. PSD/LADEE/Glenar/Guest Investigator (named on the Stubbs GI proposal)
30. PSD/LADEE/Hurley/Guest Investigator
31. PSD/LADEE/Halekas/Guest Investigator
32. PSD/LADEE//Poppe/Guest Investigator (named on Halekas GI proposal)
33. PSD/LADEE/Sarantos/Guest Investigator
34. PSD/OSIRIS REx/Marshall/Co-I and former lead of Regolith Working Group
35. PSD/OSIRIS REx/Lim*/Co-I
36. PSD/OSIRIS REx/Hartzell*/Participating Scientist
37. PSD/Phoenix/Marshall/MECA Co-I
38. PSD/MAVEN/Halekas/Co-I and lead build of ion spectrometer
39. PSD/MESSENGER/Killen/Co-I

40. PSD/Curiosity/L. Bleacher/Communications

41. PSD/Cassini/Farrell/RPWS/Co-I

42. PSD/Janus/Hartzell/Mission Scientist

43. AES/Lunar IceCube/Clark/Science P.I.

44. HSD/ARTEMIS/Halekas/Deputy P.I.

45. HSD/ARTEMIS/Delory/Co-I

46. HSD/ARTEMIS/Poppe/TM

47. HSD/WIND/Collier/Deputy P.I.

48. HSD/WIND/Farrell/WAVES and MFI Co-I

49. HSD/Parker Solar Probe/Farrell/Co-I

50. HSD/Parker Solar Probe/Schwadron/Co-I

51. HSD/IBEX/Schwadron/Co-I

52. HSD/Tracers/Halekas/Co-I and Instrument lead

53. HSD&ESA/Solar Orbiter/Collier/Co-I Heavy ion sensor (GSFC lead)

54. HSD&ESA/SMILE/Collier/Co-I

55. HSD/CuPID cubesat/Collier/Co-I and instrument lead

56. ESA/BepiColumbo/Killen/Co-I

57. DoD (Space Test Program)/FASTSAT/Collier/Co-I and instrument lead

58. DoD (Space Test Program)/USAF DSX/Farrell/Co-I and search coil build lead

5.2. Mission Consulting

5.2.1. xEVA team at JSC

- LEADER team member Farrell invited to present ‘The Lunar Plasma Environment’ in November 2019 at a Technical Interchange Meeting (TIM) team meeting.
- LEADER NPP Anthony Rasca presented at the EVA workshop in Feb 20.
- Leader team member Farrell invited to present ‘Dynamic aspects to human system charging on the lunar surface’ at Apr 20 xEVA team meeting.
- Leader team wrote section D.1.3.18 on lunar surface charging for xEVA document on the environment: EVA-CR-00077_EVA-EXP-0039 in Apr 20.
- Based on LEADER inputs, the xEVA team decided to examine dust tribocharging of human systems while roving. A document was created to perform triboelectric studies (the Electrostatic properties testing section in ‘NASA Classifications and Standards for Testing with Dust’).
- xEVA team members frequently contact LEADER team members to ask environmental questions about the Moon, including about magnetic fields, suit design, tribocharging, and the Gateway environment.

5.2.2. HLS team at MSFC (Rob Sugg’s team)

- LEADER NPP Dov Rhodes worked with MSFC/HLS team member Emily Willis on getting NASCAP spacecraft charging software operating.
- LEADER team members worked with MSFC HLS team in a foundation document ‘Lunar Plasma Environment for NASA Crewed Missions’ including a description of LEADER model results of lunar surface charging.
- LEADER team members Tim Stubbs and Bill Farrell reviewed and updated the ‘Design Specifications for the Natural Environment (DSNE)’ document (SLS-SPEC-159-Cross-program DSNE-Revision H).

5.2.3. Gateway Exosphere Instruments

- Winter of 2019-2020, LEADER Co-I Tim Stubbs led a response team to determine how the Gateway could be used as a platform to study the exosphere and dust environment. This was part of the Gateway Utilization: Request for Payload in response to a Jacob Bleacher request.
- GSFC’s Mehdi Benna and LEADER’s Farrell were part of Tim’s team coming up with concepts and reviewing his material.

5.2.4. JSC Dust chamber studies

- JSC’s Don Barker received funds to build a dust adhesion test chamber. He contacted IMPACT’s Mihaly Horanyi and LEADER’s Bill Farrell to consult on the architecture.
- Farrell frequently consults with Don on this and other topics.

5.3. Mission Concepts

1. PiPELiNE, a long-lived lunar polar rover, P.I. Hurley: This mission concept was submitted as a white paper to the Decadal Survey for Planetary Science and Astrobiology. On request from the Moon/Mercury panel on the Decadal Survey, Hurley presented to the panel the science motivation for the concept, which is based on results from LEADER (and DREAM2) research and the aggregation of understanding by many members of the lunar volatiles community.

2. Aeolus: a Mars wind observing mission, P.I. Colaprete.

3. The Lunar Dust Mitigation SDT, Chair, Christine Hartzell, is identifying and developing instruments for a future multi-user facility (analogous to the science facilities on the ISS) on the lunar surface to investigate dust-plasma interactions. The SDT is funded by BPS

and STMD. Some of the instruments focus on detecting electrostatic lofting, detecting electrostatic levitation, and characterizing the near-surface plasma environment (via Langmuir probe). Other mitigation-focused payloads include a device to assess the dust clearing efficacy of mitigation techniques, including the KSC Electrostatic Dust Shields, as well as technologies to remove dust from surfaces via induced electrostatic lofting.

4. PRISM proposals are under development (Tim Stubbs, Menelaos Sarantos, Bill Farrell).

5. Continue the development of a combined ion and neutral atom spectrometer system to study the hydrogen albedo from the lunar surface arising from solar wind input and sensing the surface conversion to surface outflowing molecular hydrogen ions, energetic atomic H, and other trace H-bearing species (Collier, McLain, Keller, Farrell).

6. Awards

1. Parvathy Prem was honored at APL's Annual Diversity Recognition Luncheon for her role in organizing a screening of the documentary "Can We Talk?" (https://www.kendallmooredocfilms.com/can-we-talk) followed by a discussion with the filmmaker, Prof. Kendall Moore.

2. Christine Hartzell received the Planetary Science Division Early Career Award in March 2020.

Network for Exploration and Space Science (NESS)

Jack Burns
University of Colorado, Boulder, CO

CAN-2 TEAM

1. NESS Team Report

1.1. Primordial Hydrogen Cosmology

1.1.1. Theoretical Predictions of the 21-cm Signal

A key goal of low-frequency radio telescopes on and near the Moon is to observe the Cosmic Dawn, the period (about 100 million years after the Big Bang) when the first stars and black holes formed. While such sources are individually far too faint to be observed directly, the radiation generated by them can be measured through the 21-cm emission line of neutral hydrogen, which pervades the Universe during the Cosmic Dawn. The lunar environment is ideal for observing this signal, because it avoids contamination by terrestrial sources and is free of distortions induced by Earth's ionosphere.

Unfortunately, the signal is still very difficult to detect, and theoretical predictions of the 21-cm signal are essential for optimizing instrument design to measure properties of the Cosmic Dawn. At UCLA, Co-I Furlanetto and his group have studied how "warm" dark matter scenarios will affect the Cosmic Dawn (Mebane & Furlanetto, in prep), offering a range of new template signals for optimizing instrumental analyses. Mebane has also developed a framework to incorporate these first stars and black holes into the popular prediction code 21cmFAST and is studying how they modify fluctuations in the signal (Mebane et al., in prep), which radio arrays on the lunar farside hope to eventually observe. Additionally, a key challenge in studying the Cosmic Dawn is in disentangling the effects of "normal" galaxies from the exotic first stars. Trapp & Furlanetto (2020) showed how future space telescopes will pin down the contributions from the former, while Furlanetto (2021) showed how "normal" galaxies evolve during this era in a new suite of models.

1.1.2. Experimental Progress

An early-career researcher (D. Lewis, B.S. 2019) analyzed long integrations acquired by the EDGES ground-based spectrometer to determine the average strength of radio recombination lines (RRLs) away from the plane of the Milky Way galaxy. RRLs are the result of electrons transitioning between very high orbital energy states within atoms in the interstellar medium. They are observed in both emission and absorption and are a potential foreground for 21cm cosmology observations. This work is the first time they have been characterized in the regions of the sky targeted by upcoming 21cm observations of Cosmic Dawn and the Dark Ages. Surprisingly, RRLs were detected when averaged across the cold regions of the sky. Results from the analysis are in preparation for publication and suggest that future 21cm cosmology observations, such as those planned by DAPPER and FARSIDE, will need to excise spectral channels where the lines occur.

1.1.3. Data Analysis Pipeline for Global 21-cm Signal Experiments

For a series of papers describing our data analysis pipeline, the second (Rapetti et al. 2020) and third (Tauscher, Rapetti & Burns 2020b) were published. Paper II presents the final step of the pipeline, in which Bayesian inference is performed to estimate the parameter probability distribution of given non-linear signal models, while analytically marginalizing over linear parameters of the beam-weighted foreground obtained following the technique described in Paper I. As shown for simulated cases, this methodology is able to recover input parameter values and properly account for statistical and systematic uncertainties. In Paper III, we show the key advantages of employing multiple correlated global 21-cm spectra at different drift scan times and/or Stokes polarization parameters. Our pipeline naturally analyzes data in this manner to leverage the fact that the beam-weighted foreground component of the data changes as a function of sky view during drift scan observations, and it is polarized, whereas the signal does not change and is unpolarized.

In another paper (Tauscher, Rapetti & Burns 2020a), assumptions in traditional global 21-cm experiments were critically examined, and problematic aspects of not sufficiently incorporating the chromaticity effects of the antenna beam on the foreground were demonstrated. In addition, a new analysis that does not assume any signal model was presented and shown to produce valuable results based solely on beam-weighted foreground modeling. Such constraints can then be used to form the likelihood function for a Bayesian inference analysis of a given signal model, without any further foreground marginalization required. In two other papers, Bassett et al. (2021) and Hibbard et al. (2020), further data analysis advances were developed, in the former, to test the goodness-of-fit of our modelling, and in the latter, to extend and compare beam-weighted foreground models.

For the Dark Ages Polarimeter PathfindER (DAPPER) mission concept, funding was pursued, received and employed for instrument and pipeline maturation.

1.1.4. Instrument Development

1.1.4.1. Advanced Receiver Development

Precise measurements in cosmology force stringent requirements on the stability and calibration accuracy of space-borne radiometers such as the type being considered for DAPPER. NESS-supported graduate student David Bordenave is advancing the state-of-the-art in correlation receiver technology to meet these goals. The correlation receiver, first introduced to radio astronomy in the 1960s, was known for its sensitivity and stability. David is improving upon these attributes by modernizing the electronics and extending its capabilities through a novel, four-channel configuration for the analysis of the E-field polarization characteristics of the incoming radiation. The initial prototype of this receiver is being developed to measure the absolute sky brightness at 310 MHz using the clear-aperture radio telescope in Green Bank, WV, but it will eventually be used with this telescope to produce a high-accuracy, polarization sky map at this frequency, a critical input to the DAPPER data analysis pipeline. The second version, operating from 60-110 MHz, is currently under development at NRAO for DAPPER.

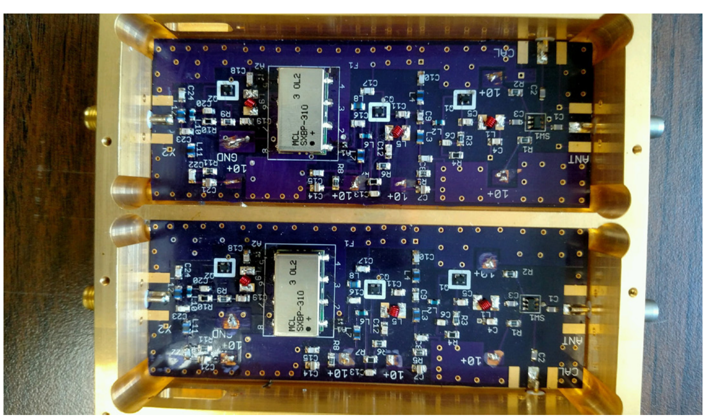


Figure 1: Photo of the initial DAPPER/CTP prototype receiver module. A full dual polarization version with noise calibration was assembled and is ready for correlation tests.

1.1.4.2. FARSIDE Concept Instrumentation

As part of the FARSIDE concept development, a graduate student at ASU (N. Mahesh) has begun investigating the polarization properties of the array. Conventional antennas used in radio astronomy have the phase centers of each of the two polarization elements co-aligned. FARSIDE, however, will have offset phase centers for its two polarization elements due to including both of its polarization dipoles sequentially on a single tether deployed by a rover. This creates a unique response pattern for the FARSIDE antennas that must be accounted for during image processing. Initial results suggest that the FARSIDE polarization properties introduce manageable effects into the instrument response. Over the next year, we plan to expand the investigation to fully simulate FARSIDE observations, including realistic sky and antenna models.

1.2. Surface Telerobotics

Immersion provided by virtual and mixed reality (VMR) head-mounted display (HMD) robotic interfaces improves efficiency and situational awareness without increasing the workload of operators. To fully examine the capabilities that HMD technologies afford in the construction of radio telescopes on the Moon, CU graduate student M. Walker, supervised by D. Szafir and J. Burns, is examining multi-perspective VMR HMD interface designs. Egocentric (1st person) and exocentric (3rd person) designs are being explored to examine overall effectiveness, as well as optimal use cases for either design paradigm. By combining the design concepts seen in 1st person virtual control room interfaces (Figure 2) and 3rd person cyber-physical interfaces, we hypothesize interfaces will offer

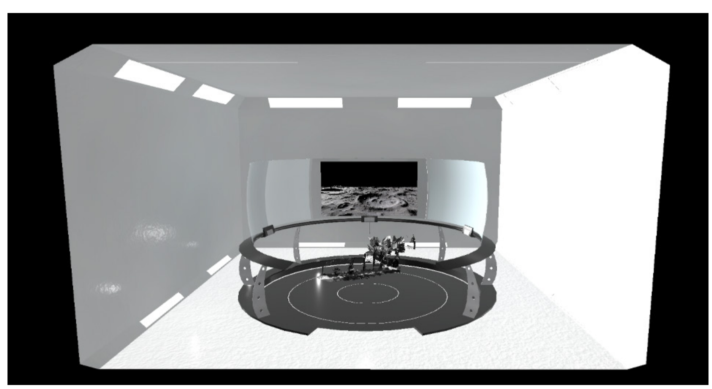


Figure 2. The CU prototype mixed reality robot teleoperation interface that presents both an egocentric 3D video stream and an exocentric 3D reconstruction to operators.

significant operational advantages when a robot operator on the Moon can simultaneously access both egocentric and exocentric perspectives. We are investigating how this type of combined interface can facilitate group collaboration during mobile robot teleoperation/ supervision planning and live missions by rendering virtual telepresence user avatars that share the virtual space within the interface.

A sustainable lunar presence permits low-latency robotics, which enable missions such as the FARSIDE array. The mission design requires a teleoperated rover to deploy antenna nodes from its lander onto the lunar surface. These types of lunar missions leveraging human-robot interactions will require new methods of robotic failure recovery. Using stereo imaging capabilities, CU students M. Bell and P. Curlin, under the supervision of Burns, are creating virtual/augmented reality interfaces for both teleoperation and simulated failure recovery. By developing our virtual recovery sandbox (Figure 3), we can create a virtual space representative of the rover's current state and environment. This provides the ability to troubleshoot problems as if the operator were next to the rover itself, in an exocentric perspective. If proven to support teleoperated failure recovery, this sandbox may be leveraged in a variety of robotic applications. We plan to compare our model with traditional control and failure recovery methods, with the focal point on construction of lunar telescopes.

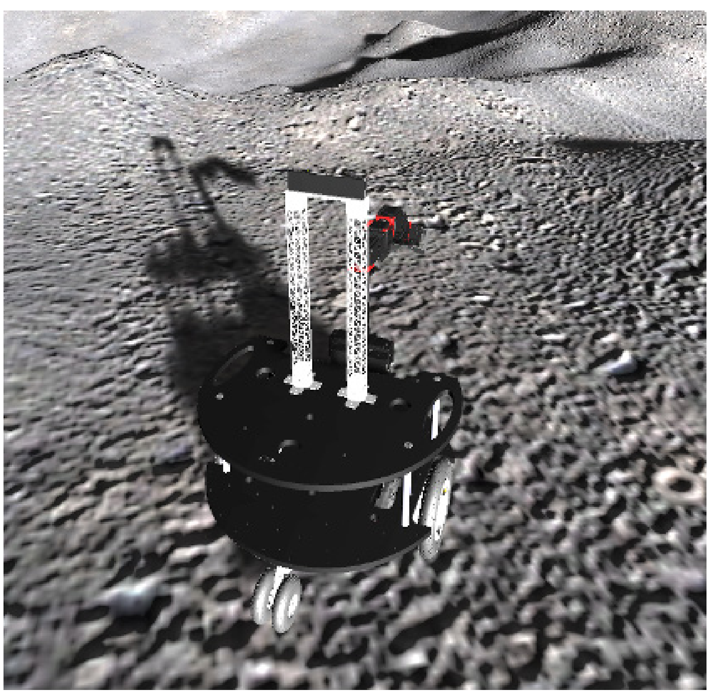


Figure 3. The Armstrong rover viewed from the exocentric standpoint, within the virtual recovery sandbox; A risk-free virtual solution development environment.

Virtual planetary environment simulators provide a fast, flexible, and cost-effective alternative to field analogs for generating datasets for algorithm design/testing, operations planning, operator training, and mission mock-ups. At CU, postdoc M. Menon, along with Walker, Szafir, and Burns, have developed a scalable and modular simulation framework that generates photometrically accurate lunar virtual environments. The framework renders the environment using the Unity game engine and integrates with the Robotic Operating System (ROS) to simulate the robots interacting with the environment. The lunar topography with high-resolution terrain is modeled by overlaying Digital Terrain Models generated from Lunar Reconnaissance Orbiter-Narrow Angle Camera (LRO-NAC; see Figure 4). We modelled the robotic systems as ROS nodes, which accept inputs from simulated sensors like stereo cameras, LIDAR, and an Inertial Measurement Unit (IMU). We incorporated dynamic tessellation to the terrain, making the simulator memory-efficient yet capable of adding details like wheel tracks. Using FARSIDE as our case study, we are working on a navigation algorithm called Simultaneous Localization And Mapping (SLAM). We will carry out a comprehensive comparative study and will use the results to design navigation and teleoperation algorithms specific to Moon.

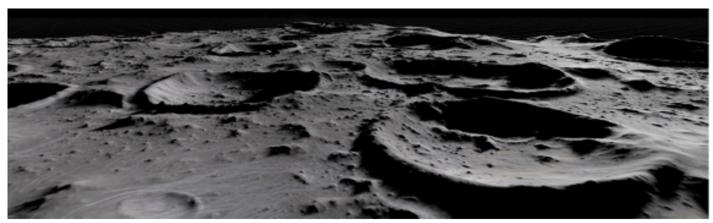


Figure 4. Synthetic lunar terrain developed using LRO-NAC images.

1.3. Heliophysics

Co-I Kasper and Collaborator Hegedus have progressed on the Sun Radio Interferometer Experiment (SunRISE) mission formulation. SunRISE is a Heliophysics Mission of Opportunity that is currently in Phase B. SunRISE will consist of 6 CubeSats with radio receivers that together form an interferometer. SunRISE will circle the Earth in a GEO graveyard orbit and sample the low radio frequency range 0.1-20 MHZ and make rudimentary images below the ionospheric cutoff for the first time. Data will be recombined on the ground, forming a synthetic aperture. SunRISE's primary science is to localize type II radio bursts within coronal mass ejections (CMEs) to identify the site of particle acceleration of solar energetic particles (SEPs), as well as to map the trajectories of energetic electron packets associated with type III bursts. Hegedus has also shown through robust modeling of the data processing and science analysis pipelines that SunRISE will be able to discern between different possible acceleration regions, even those that result in similar Type II burst structure in frequency and time from individual antenna measurements. Figure 5 displays a summary of these results, showcasing a SunRISE case study using a 05/13/2005 CME. In the upper left is real radio data from the Wind/WAVES antenna showing the powerful type II radio burst from the 2005 CME. The type II burst can be seen as the red, less intense descending emission starting around 1 MHz, after the white, more intense type III burst that descends far more quickly. In the upper right is a snapshot from an Alfven-Wave driven Solar wind Model (AWSOM) MHD simulation of the 2005 event with the shock identified from the entropy ratio. The lower left shows synthetic spectra made from the identified shock in the MHD data with the dashed white line identifier from the real spectra above. Note that this is a column normalized histogram of points with upstream plasma frequency in the specified radio range, not true brightness spectra. In the lower right are SunRISE reconstructions of the progression of the type II radio burst, with a hypothesized truth image coming from the identified shock in the MHD simulation, using a subselection of the entropy derived shock front on the eastern edge of the shock on the left. Each colored ellipse corresponds to a SunRISE reconstruction of the simulation derived input for each frequency channel over time, tracing out the path of the emission.

1.3.1. Instrument Development

1) Radio wave Observations at the Lunar Surface of the photoElectron Sheath (ROLSES) is a NASA-Provided Lunar Payload to place a radio frequency spectrometer on the

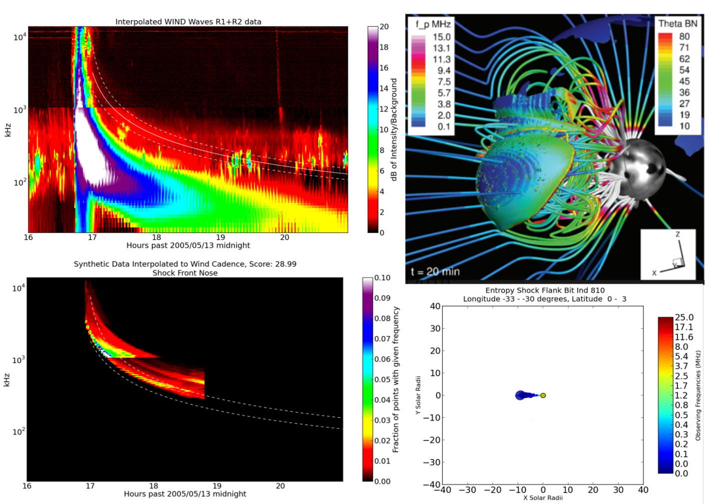


Figure 5. SunRISE case study using a 05/13/2005 CME (see details in the text); modeling of the data processing and science analysis pipelines indicate that SunRISE will be able to discern between different possible acceleration regions.

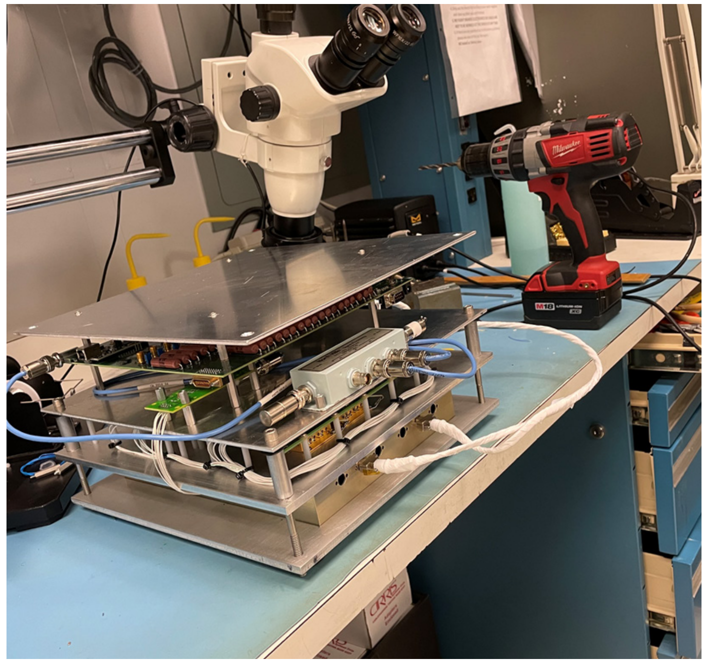


Figure 6. The ROLSES payload will undergo flat-sat testing at Intuitive Machines in January 2021; since the payload is not completed, the relevant data and power boards and a data simulator will be tested in the stack shown above.

lunar nearside. NESS member Bob MacDowall is the P.I., and Jack Burns and Michael Reiner were other NESS team members on the proposal. ROLSES will provide information about the electron density from 1 to 3 m above the surface, which is relevant information for other lunar surface radio observatories. It will also work to get radio data that will relate to several science and technical goals. ROLSES will go to the lunar surface on the Nova-C lander of Intuitive Machines. Flat-sat testing will take place in January 2021. Figure 6 shows the ROLSES boards stack readied for flat-sat testing in December 2020. The intuitive Machines new plan will now have the Nova-C lander go to Oceanus Procellarum in November 2021.

2) Lunar Surface Electromagnetic Experiment (LuSEE) is a NASA LISTP lunar payload set of instruments, proposed by Stuart Bale, U.C. Berkeley, with several NESS team members included on the proposal. It is a unique LISTP payload, because it is almost a duplicate of the Parker Solar Probe FIELDS instrument suite, which measures magnetic, DC electric, radio, and other data. Therefore, LuSEE's goals are to: (i) measure the DC electric and magnetic fields, including plasma waves; (ii) measure electrostatic signatures of dust impacts; (iii) measure radio emissions from the Sun, Earth and outer planets; (iv) address the formation and structure of the lunar photoelectron sheath and the interaction of the lunar surface with plasma from the solar wind and terrestrial magnetotail; (v) probe the structure and dynamics of the

tenuous lunar exosphere. Although it still doesn't have a lander assigned yet, the plan is to go to the Schrödinger crater near the lunar south pole on the farside. The GSFC MAG team, led by NESS team member Bob MacDowall, will provide the fluxgate magnetometer for LuSEE.

1.4. Extrasolar Space Weather

The detection of exoplanetary radio emission, as well as the detection of stellar radio bursts indicative of coronal mass ejections (CMEs) and stellar energetic particle events (SEPs), is critical for diagnosing planetary habitability and understanding the role that planetary magnetospheres play in shielding their atmospheres from the space weather environments of their host stars. Lunar-based low-frequency radio telescopes are vital for expanding our reach beyond the Jovian-like magnetospheres that are accessible from the ground to the terrestrial-like magnetospheres that can only be detected from space.

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA, led by NESS Co-I Hallinan) is a ground-based array that serves as a pathfinder to future lunar-based low-frequency radio arrays (e.g. FARSIDE), providing a framework for the operation and design of a survey targeting extrasolar space weather science from the lunar surface. OVRO-LWA targets nearby stellar systems to monitor for stellar CMEs and SEPs, as well as radio signatures of planetary magnetospheres — specifically, the Jovian-like magnetospheres that are detectable from within Earth's ionosphere. The OVRO-LWA is a 288-element dipole array in California (see Figure 7), operating at sub-100 MHz frequencies and imaging the entire viewable hemisphere at 10-second cadence. This allows for the simultaneous monitoring of thousands of stellar sources for radio emission indicative of space weather events. The Caltech team led by Hallinan, which also includes JPL postdoc and NESS team member Marin Anderson, is analyzing the 1000 hours of OVRO-LWA data that was collected prior to the decommissioning of the Phase II array in February 2020. The data span 33–48 MHz, ideal for targeting a sample of hot Jupiters for auroral radio emission. The OVRO-LWA data also overlap with observations from NASA's Transiting Exoplanet Survey Satellite (TESS), providing unprecedented simultaneous optical and low radio-frequency coverage of a sample of nearby (< 25 pc) stars in order to search for evidence of CMEs associated with large flares detected in the optical band. Results from this 1000-hour dataset with OVRO-LWA will be published in 2021.

Work has also begun on Phase III of the OVRO-LWA, which will expand the existing array to its final configuration of 352 dipoles spanning a 2.6 km diameter area, providing 5 arcminute spatial resolution at the top of the band. Work on the Phase III array also includes a full redesign of the analog and digital signal processing systems, as well as efforts to measure the individual beam patterns of all 352 dipole antennas via multiple methods (including via drone). The latter of these will be a relevant step in demonstrating the capability of mapping FARSIDE dipole antennas via an orbiting calibration beacon. Precise knowledge of the antenna gain pattern is essential for achieving the sensitivity necessary for detecting extrasolar space weather events.

Figure 7. Looking east from the center of OVRO-LWA, a dipole array in California operating at sub-100 MHz frequencies images the entire viewable hemisphere to simultaneously monitor thousands of stellar systems in search of stellar and planetary radio emission.

2. Inter-team/International Collaborations

Collaborator Hegedus was a Co-I on two proposals in the European Space Agency's Call For Ideas, "Exploring the Moon with a large European lander." One was inspired by his recent paper in Radio Science, "Measuring the Earth's Synchrotron Emission From Radiation Belts With a Lunar Near Side Radio Array" with European co-author Baptiste Cecconi from Observatoire de Paris submitting the step 1 proposal titled "Van-Allen Belts Imaging from the Moon (VABIM)." The other proposal was titled "Sunbeam (Sun Bursts Explorer by Radio Array on the Moon)," with the lead being Antonio Vecchio from Radboud University in the Netherlands.

Burns was a collaborator on a successful ESA concept study proposal called LunarLOFAR. This is a low frequency radio array from the lunar farside with elements in common to the NESS FARSIDE concept. Over this next year, we will be investigating a potential ESA/NASA collaborative study of a lunar low frequency radio array including the science cases for the instrument.

Co-I Fong participated in the "International Space Station as a Mars Mission Analog: A Virtual International Workshop on Innovative Research and Operations Approaches." The purpose of this workshop was to bring together international strategic leaders in human spaceflight (NASA, CSA, ESA, JAXA, etc.) to develop creative approaches to using the ISS as an analog for preparation for Mars missions to be implemented in its 3rd decade of operations. Fong provided recommendations for the use of robots in transit, particularly for performing in-flight maintenance and augmenting crew situation awareness.

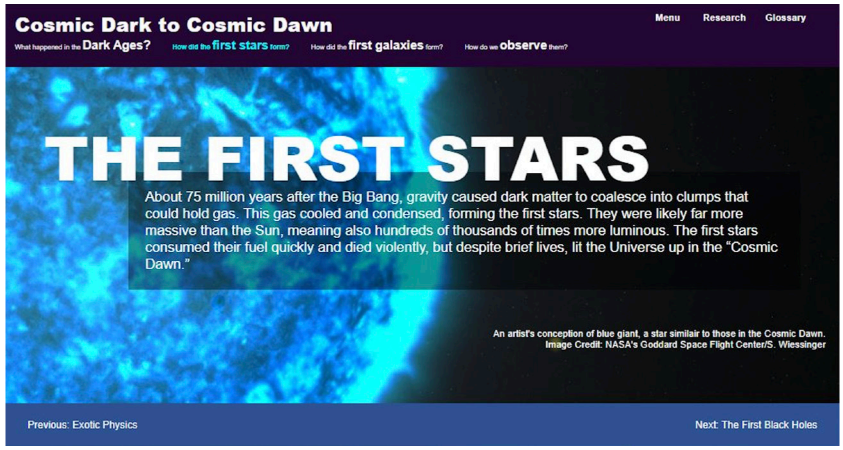


Figure 8. Excerpt of a draft science overview page from the Cosmic Dark to Cosmic Dawn outreach website. The menu at the top identifies key questions to engage readers. Each science page includes a short overview for readers; further down on each page, the key questions will be addressed in more detail.

3. Public Engagement

3.1. From Cosmic Dark to Cosmic Dawn: An Outreach Website

Lunar radio arrays promise transformational science in our understanding of cosmology. They will provide the most sensitive probe available of exotic physics in the early Universe, and they will provide the most sensitive studies of the formation of the first stars and black holes during the Cosmic Dawn. This science is so new that very little of this promise has filtered out to the public. As part of NESS's outreach effort, the UCLA group is leading the development of an outreach website to help fill this gap. Co-I Furlanetto and undergraduate student Erika Hoffman have made significant progress on developing the first phase of the website this year.

The website, titled Cosmic Dark to Cosmic Dawn, will provide a comprehensive overview of the science we can learn from these studies as well as the technology behind the many telescopes that will study this era. The first phase (which we hope to make public in spring 2021) is aimed at the "educated lay person" enthusiastic about popular science. We are leveraging the nonlinearity of websites to allow viewers to engage in multiple ways: following the technology or the science, diving deep into particular topics, or following the timeline for a quick overview. The site will have pages on major science topics (such as the First Stars; see draft version in Figure 8, which shows the introductory section of this page), telescopes, and key concepts. We will take full advantage of hyperlinks to cross-reference related topics and provide background whenever possible.

3.2. Planetarium Show: Forward! To the Moon

In coordination with NESS and Lockheed Martin, Fiske Planetarium at the University of Colorado Boulder has produced a 6-minute prologue to a 25-minute full-dome film that will be released in Summer 2021 entitled Forward! To the Moon (Figure 9). The full-length film features the NASA Artemis Mission, with emphasis on the Space Launch System, the Orion Crew Vehicle, the Gateway, and telerobotic lunar research that will be enabled by these efforts. The film also includes interviews with NASA astronauts from the Artemis Team, as well as testimonials from engineers associated with robotic lunar science efforts. Forward! concludes by highlighting the import role that lunar research will play in future plans for human exploration of Mars.

Fiske Planetarium hosts a network of over 300 planetarium facilities that regularly download free full-dome content such as Forward! Promoted through this network along with the NASA Museum Alliance, Fiske hosted a virtual preview of the film prologue for planetarium and museum directors and staff in October 2020. This event, which

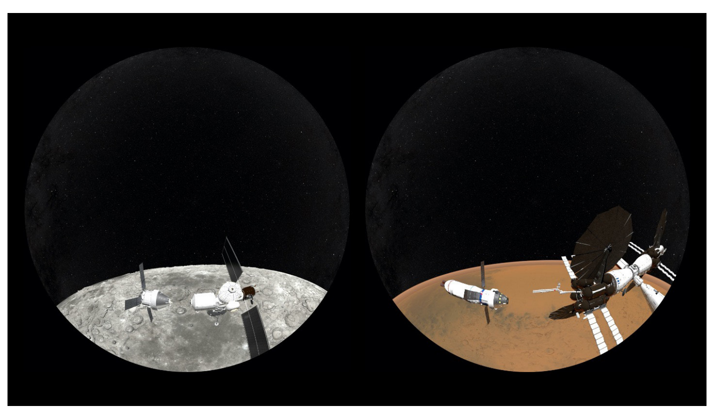


Figure 9. Fisheye projections of two scenes from the full-dome film Forward! To the Moon. Image to the left shows the Orion spacecraft docking with the Lunar Gateway. Image to right shows Orion docking with the Mars Basecamp.

included presentations by NASA Chief Scientist Jim Green, SSERVI Director Greg Schmidt, NESS Director Jack Burns, Fiske Director John Keller, and film narrator Kari Byron (from Mythbusters and Crash Test World), was attended by over 60 planetarium and museum representatives. The full-length film will premiere at Fiske Planetarium in late summer 2021, along with a film tour at several large planetariums across the US, and will be available free of charge to facilities of all sizes across the globe.

4. Student/Early Career Participation

Undergraduate Students

1. Erika Hoffman (UCLA, beginning June 2020): outreach website designer

2. Phaedra Curlin (University of Colorado Boulder): surface telerobotics

3. Mason Bell (University of Colorado Boulder): surface telerobotics

4. Olivia Seidel (Maharishi International University, virtually visiting CU Boulder, Summer-Fall 2020): 21-cm data analysis studies

Graduate Students

5. Richard Mebane (UCLA, until October 2020): theoretical 21-cm studies

6. Adam Trapp (UCLA): theoretical 21-cm studies

7. David Bordenave (Department of Astronomy, University of Virginia): experimental 21-cm studies

8. Neil Bassett (University of Colorado Boulder): 21-cm data analysis studies

9. Joshua Hibbard (University of Colorado Boulder): 21-cm data analysis studies

10. Keith Tauscher (University of Colorado Boulder, until August 2020): 21-cm data analysis studies

11. Michael Walker (University of Colorado Boulder): surface telerobotics

12. Nivedita Mahesh (Arizona State University): experimental 21-cm studies

Lab Technicians

14. David Lewis (graduated and currently working as a lab technician at Arizona State University before potentially starting graduated studies): experimental 21-cm studies

Postdoctoral Fellows

15. Alexander Hegedus (University of Michigan): simulating space-based radio arrays

16. Marin Anderson (California Institute of Technology, Jet Propulsion Laboratory): extrasolar space weather

17. Steve Murray (Arizona State University): 21-cm data analysis studies

18. Midhun Menon (University of Colorado Boulder, until Fall 2020): surface telerobotics

19. Jordan Mirocha (McGill University): theoretical 21-cm studies

20. Bang Nhan (National Radio Astronomy Observatory): experimental 21-cm studies

21. Keith Tauscher (University of Colorado Boulder, from August 2020): 21-cm data analysis studies

22. John Keller (Fiske Director, previously joined in connection with the Planetarium show): public engagement

New Faculty/Staff Members

23. David Rapetti (in September 2020, transition from Visiting Scientist to Scientist at NASA Ames Research Center/Universities Space Research Association; also affiliated with the University of Colorado Boulder): 21-cm data analysis studies

6. Mission Involvement

1. **SunRISE:** Kasper and Hegedus have progressed on the Sun Radio Interferometer Experiment (SunRISE) mission, a Heliophysics Mission of Opportunity that is currently in Phase B. SunRISE will consist of 6 CubeSats with radio receivers that together form an interferometer. SunRISE will act as a pathfinder for future space-based radio arrays like FARSIDE, producing the first basic maps of the low frequency sky and localizing bright transient emission from solar eruptions.

2. **FARSIDE:** Burns and Hallinan are P.I. and Deputy P.I., respectively, of the Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE), which is a Probe-class concept to place a low radio frequency interferometric array on the farside of the Moon. The final Probe-class concept study, completed in partnership with JPL, was submitted to NASA at the end of 2019. Since that study, the FARSIDE design has continued to advance, with the selection of the Blue Moon Lander via the partnership with Blue Origin. The initial design proposed in the study was a single rover for deployment of antennas along a four-petal configuration. This design has evolved into four JPL axel rovers for deployment of antenna-embedded tethers in a four-spiral arms configuration. This redesign significantly reduces the risk posed by the failure of the single deployment rover, as well as mitigates the impact on imaging performance in the event of a single spiral arm failure.

3. **DAPPER:** Burns is P.I. of the Dark Ages Polarimeter PathfindER (DAPPER) mission concept. The early Universe's Dark Ages, probed by the highly redshifted 21-cm neutral hydrogen signature averaged over the entire sky, is an ideal epoch for a new rigorous test of the standard LCDM cosmological model. DAPPER, operating in the radio-quiet farside, shall search for divergences from the standard model that will indicate new physics such as heating or cooling produced by dark matter, as well as investigate the astrophysics of the first stars, galaxies and black holes in the Cosmic Dawn. A lunar surface version of DAPPER is being proposed to PRISM for deployment in the Schrödinger basin on a lander that will also carry the LuSEE radio science experiment.

4. **VIPER:** Fong is the Deputy Rover Lead for the "Volatiles Investigating Polar Exploration Rover" (VIPER) mission. VIPER is planned to launch in late 2023 and will spend 100 days mapping and surveying four different ice stability regions in a high-latitude area of the Moon. The primary mission objective is to understand the nature and distribution of water and volatiles already confirmed to be there, including measuring mineralogical content such as silicon and light metals from lunar regolith.

7. Awards

NESS Co-I Dr. Richard Bradley received the 2020 NRAO Director's Distinguished Performance Award: "Rich has made exceptional, unique, and lasting contributions to NRAO's mission for over 30 years. His body of work covers a broad area of activities, including applied research and engineering, service to the greater scientific community, and teaching and mentoring students."

Resource Exploration and Science of Our Cosmic Environment (RESOURCE)

Jennifer Heldmann
NASA Ames Research Center, Mountain View, CA

CAN-3 TEAM

1. RESOURCE Team Report

1.1. Characterization of Resource Inventories of SSERVI Target Bodies

The RESOURCE Task 1 team is collaborating with several efforts to increase understanding of the distribution of volatiles at the lunar poles. Co-Is Hurley (Johns Hopkins University / Applied Physics Lab) and Co-Is Colaprete and Kleinhenz (NASA) supported the NASA Lunar Water ISRU Measurement Study (LWIMS) to define meaningful reference cases of the distribution of water ice in lunar polar cold traps. Presently, detailed measurements do not exist on spatial scales relevant for planning extraction of water ice as a resource on the Moon. However, using our current understanding of the processes that contribute to the distribution of water in lunar Permanently Shadowed Regions (PSRs) and constraints from data on larger spatial scales, we devised multiple potential distributions of water ice. These reference cases provide technology developers with sufficient information to aid in their design and analysis of ISRU equipment before we have specific survey data on the spatial scales needed. We also developed a summary of the current state of knowledge regarding lunar polar volatiles and presented these results to the National Academies Committee on Planetary Protection in support of their study on the potential planetary protection issues for lunar exploration.

> RESOURCE provides scientific analysis regarding the distribution and character of water ice and other volatiles in lunar PSRs which is enabling for defining planetary protection requirements for exploration and ISRU design reference missions.

1.2. Advanced Mission Operations Capabilities

Mission control operations are the "nerve center" of all space missions, and are the central environment where data is analyzed, collaboration between mission staff is enabled, and decisions are made. Virtual Reality (VR) platforms provide the opportunity to "close the loop" on mission operations by yielding a set of tools for rapid collaborative decision making to occur in an entirely virtual environment. The Massachusetts Institute of Technology (MIT) team has set out to bring a suite of virtual tools for data analysis and planning support through reward function learning in the context of simulated mission operations. The Virtual Mission Simulation System (vMSS) is a VR platform currently under development and testing to determine integration and usability pathways for data display, collaborative analysis, and rapid decision making.

> RESOURCE is developing rapid, collaborative science decisioning support tools for lunar science and exploration missions.

RESOURCE activities underway to determine the preliminary development pathway from vMSS include:

- Determine the integration pathway for two main geological instruments into vMSS. We focus on two flight instruments that are manifested on multiple NASA flight missions by RESOURCE Co-Is:

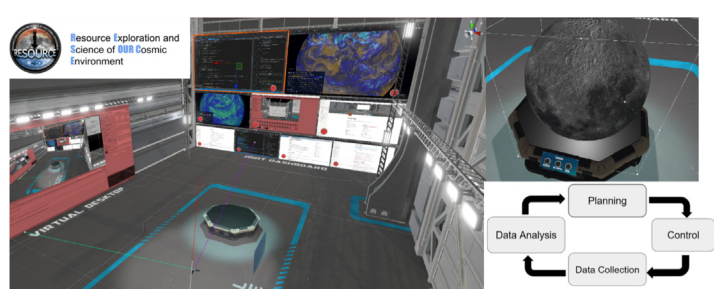


Figure 1. Virtual Mission Simulator System developed at MIT.

- o Near InfraRed Volatiles Spectrometer System (NIRVSS)
- o Neutron Spectrometer Subsystem (NSS)

- Incorporate comments from scientists working previous analogs and on current lunar missions. We are focusing on pre-mission mapping of a priori data for improved situational awareness, layering of analyzed instrument data, correlative mapping and interactive capabilities for in-mission decision making, as well as archiving, and annotation tools for post-mission analysis. We aim to provide a valuable visualization tool focusing on improving situational awareness, decision making and reducing task load.

We are also exploring algorithmic techniques for an active reward learning agent to query scientists about planning examples that are informative for the planning support system across the whole mission but also give information about tasks that are most likely to be encountered in the upcoming planning horizon, enabling more efficient in-time learning. The system can use the learned reward function to optimize the science team's objectives and suggest plans. We have begun to develop a technique for a single responder and are also exploring how to expand our work to account for multiple responders with differing preferences across the team. These approaches include novel capabilities using Artificial Intelligence (AI) for mission science planning.

> "Mission science planning is formulated as a reward learning problem where the science team has a reward function representing their priorities, and an Artificial Intelligence (AI) planning support system learns this reward function to enable rapid science decision-making."

1.3 Human-Technology Interfaces

The RESOURCE program includes social science research methods to investigate human-technology work for conducting science and exploration in extreme environments. Specifically, work ethnography research practices for data collection and analysis, which have been successfully applied in a NASA mission and analog programs, are employed in this project.

For planned 2020 RESOURCE field expeditions (delayed due to COVID-19 restrictions) to test science, technology, and operations for ice and volatile mapping and characterization, Co-I Mirmalek planned for human subjects research on decision-making activities, and for technology development to collect observations on instrument use and instrument data flow among robotic lunar prospecting teams. This work would examine the interplay between instruments, data acquisition, data dissemination, and associated decision-making in (and across) the dynamic environmental field conditions. Qualitative methods would be the primary method for data collection, specifically work ethnography would be used to guide data collection and analysis for understanding specific affordances and constraints of analog work system design, interactions among people and technologies, and workgroup communication. Analysis would be offered to all participants with respect to interest in developing work support (e.g., technology and communication) and fed forward to development for future missions or analogs.

1.4 ISRU Water Processing Plant

The RESOURCE project is working to process extracted water in an ISRU plant and demonstrate an integrated test of the critical components needed to capture, clean, deionize, and electrolyze water as well as dry the oxygen and hydrogen gas products. The leading technology for water electrolysis is based on proton exchange membranes that require deionized water. Therefore, any water derived from the lunar surface will likely require purification and deionization before it can be electrolyzed. Over the course of the past year, the focus of the NASA Johnson Space Center (JSC) team was to evaluate potential contaminants released during lunar polar regolith heating. Volatiles and particulates are the two sources of contamination that will affect the requirements of a water cleanup system. Two separate test programs were conducted to quantify the contributions of each contamination source.

For the particulate contamination test, the NASA JSC team mixed deionized water with LHT-2M lunar regolith simulant and placed it in a sealed pressure vessel (Figure 2). The hydrated regolith simulant mixture was heated to produce water vapor that was captured in a cold trap. The condensate product was then sent to two separate

Figure 2. NASA JSC thermal chamber and simulant pressure vessel.

labs, one lab performed a particle count analysis, while the other performed a chemical analysis. Three tests were performed without a filter, and three tests were performed with a 0.5 micron sintered metal filter welded into the lid of the pressure vessel. The test stand was flushed with deionized water between each test to prevent cross contamination. The requirements defined for the ISS Oxygen Generation Assembly (OGA) system were used as a guide for acceptable levels of particulate and constituents. As water vapor is released in regolith, it can create small fluidized bed channels, and the velocity of the released vapor is sufficient to entrain fine particles that can be carried to the condenser and affect the purity of the product water. The particle count analysis results showed that without a filter in place, enough fine particulate was carried downstream to the condenser that the water would not be suitable for electrolysis. However, water that passed through the 0.5 micron filter while in the vapor state resulted in a condensate product that was within the particulate tolerance limits of the ISS OGA. The chemical analysis showed that the levels of calcium, iron, and magnesium detected in the product water were within ISS OGA requirements both with and without filtration. However, the chemical analysis also revealed high levels of ammonia which had a direct correlation to the product water conductivity. Since the presence of ammonia in the simulant prevented the team from being able to derive a direct correlation between particulate and conductivity, this test will be repeated in the future with pre-baked simulant to remove ammonia as a variable.

For the volatiles contamination test, the JSC team worked with Paragon Space Development Corp to analyze water samples that were produced through freeze distillation of a mixed volatile gas stream. The Paragon team used internal funds to develop a freeze distillation system in support of their ISRU-derived water purification and Hydrogen Oxygen Production (IHOP) project. The Paragon team used LCROSS data to prepare a humidified volatile gas stream that contained carbon monoxide, hydrogen, hydrogen sulfide, ammonia, sulfur dioxide, methane, and methanol. The mixed volatile stream was sent to a cold trap that captured water vapor in the form of ice. The water ice samples were sent to JSC for chemical analysis. The results show that freeze distillation will provide a significant purification step, but additional cleanup will still be required to fully remove the volatiles that are captured within the ice. This information will be used to develop a water deionization system that accounts for the presence of volatiles that remain after freeze distillation.

> "RESOURCE hardware testing shows that filtering is required to remove fine particulates before processed water reaches a condenser in order to be suitable for subsequent electrolysis for ISRU."

1.5 Lunar Drilling Technologies

In 2020, the RESOURCE team has been focused on developing technologies for advancing In-Situ Resource Utilization (ISRU) for the Moon and pave the way for advancing these technologies for other Solar System bodies, including Mars. The technology we highlight here is The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) ice mining drill for two exploration/ ISRU missions to the Moon: Polar Resources Ice Mining Experiment (PRIME-1) and the Volatiles Investigating Polar Exploration Rover (VIPER). PRIME-1 is scheduled to fly to the Moon in 2022 while VIPER is targeting launch in 2023. Both missions are targeting the lunar south polar volatile rich deposits.

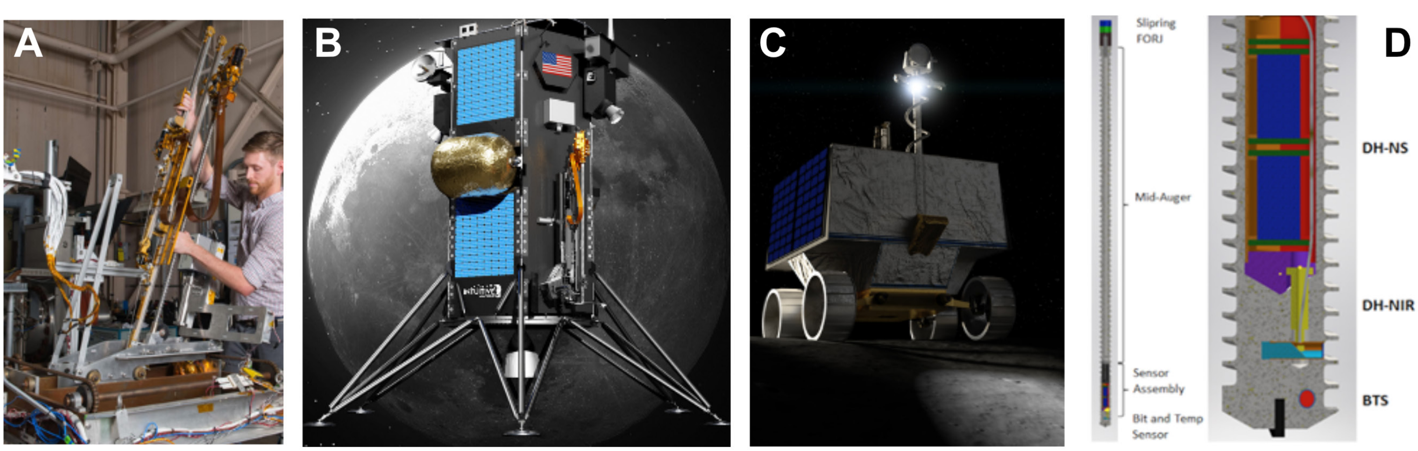


Figure 3. (A) TRIDENT drill undergoing TVAC tests at NASA GRC. (B) PRIME-1 mission. TRIDENT is vertically mounted on the righthand side of the Intuitive Machines (IM) lander. (C) VIPER mission. TRIDENT is placed in vertical position in the middle of the rover. (D) Instrumented auger with Down Hole Near Infrared Spectrometer (DH-NIR) and Down Hole Neutron Spectrometer (DH-NS).

The primary goal of TRIDENT is to deliver volatile-rich samples from depths up to 1 m to the lunar surface (Figure 3). Once on surface, the material would be analyzed by Mass Spectrometer Observing Lunar Operations (MSolo) and the Near InfraRed Volatiles Spectrometer System (NIRVSS) to determine volatile composition and mineralogy of the material. MSolo will fly on both missions while NIRVSS will fly on VIPER and another Commercial Lunar Payload Services (CLPS) mission.

TRIDENT is a rotary-percussive drill which enables it to cut into icy material that could be as hard as rock. To reduce thermal risks, risk of getting stuck, reduce drilling power, and provide stratigraphic information, the drill will capture samples in 10 cm bites, meaning the drill will drill 10 cm at a time and bring up 10 cm worth of material to the surface.

In addition of being a tool for providing samples, TRIDENT is also an instrument. TRIDENT drilling power and penetration rate is used to determine regolith strength. TRIDENT's integrated heater and temperature sensors measure downhole temperature and could provide thermal conductivity. These two measurements, temperature and thermal conductivity, are needed to determine heat flow properties of the Moon. TRIDENT will also be able to provide bearing capacity data of the top lunar surface.

TRIDENT's downhole heater and temperature sensors pave the way for more advanced downhole technologies that are being developed under the RESOURCE project. The goal is to integrate the neutron spectrometer and near infrared spectrometer, e.g., the Neutron Spectrometer System (NSS) and NIRVSS instruments, respectively, into the drilling auger. This advancement would change the paradigm of planetary exploration: instead of bringing a sample to an instrument we would be bringing an instrument to a sample.

Having NSS and NIRVSS integrated into the auger would allow unprecedented increase in science data: the instruments will be able to look at minimally disturbed samples and increase stratigraphic resolution. Initial designs show that integrating both of those instruments is feasible.

2. Inter-team/International Collaborations

RESOURCE is pleased to partner with multiple inter-team and international SSERVI partners. These partnerships have led to important contributions to the RESOURCE portfolio.

2.1. International Collaborations

2.1.1. Canadian Lunar Research Network, University of Western Ontario

RESOURCE works closely with team member Dr. Gordon Osinski (University of Western Ontario, UWO) as the lead of the Canadian Lunar Research Network, an official SSERVI international partner. RESOURCE specifically capitalizes on the expertise of UWO in terms of ice and volatile characteristics and behavior in cold environments in order to understand ice deposits on the Moon. UWO has also contributed to RESOURCE planning for terrestrial analog testing of science, operations, and technologies as relevant for ice characterization, and provides key inputs for terrestrial analog deployments.

2.1.2. Korea Institute of Geoscience and Mineral Resources (KIGAM)

RESOURCE Collaborator Dr. Kyeong Kim is a researcher with the Korea Institute of Geoscience and Mineral Resources. Kim's research focuses on lunar science and the applications of XRF analysis on planetary surfaces. Kim is also the P.I. of the gamma ray instrument slated to fly onboard the Korean Pathfinder Lunar Orbiter (KPLO) and has involved RESOURCE team member R. Elphic as a Co-I with KPLO.

2.1.3. Curtin University, Perth, Australia

RESOURCE Collaborator Dr. Phil Bland provides a direct connection between the RESOURCE team with the Australian mining industry. In particular, RESOURCE capitalizes on Australia's vast mining industry regarding best practices and technologies for optimal mining protocols to enable planetary ISRU.

2.1.4. Open University, United Kingdom

RESOURCE Collaborator Dr. Mahesh Anand is a recognized expert in lunar ISRU. Specifically, Dr. Anand's expertise is valuable for helping help assess mineral and chemical resources on the Moon.

2.2. SSERVI Inter-Team Collaborations

2.2.1. RISE2

The RESOURCE P.I. has coordinated with RISE2 P.I. to establish and run the NASA / SSERVI Analogs Focus Group. This Focus Group capitalizes on the expertise of these two SSERVI teams and integrates the capabilities and needs of the broader community to provide a forum for timely discussion and advancement of analog field activities to support both human and robotic exploration of SSERVI target bodies.

2.2.2. GEODES

The RESOURCE project, through the Analogs Focus Group, has chosen to highlight SSERVI GEODES field science to the broader science and exploration communities. The GEODES P.I. was invited to give an Analogs Focus Group seminar which was presented live and also remains archived on the SSERVI Focus Group website for later viewing.

3. Public Engagement Report

3.1. Broadening Community Participation

The RESOURCE Science Activation and Public Engagement (SA/PE) team, led by Co-I Matiella Novak at Johns Hopkins University / Applied Physics Lab, is continuing with its efforts to engage educators, students, and broaden participation among underrepresented groups. This includes collaborating with various partners, both internal and external to SSERVI. Currently our activities are focused on increasing representation through educator and Subject Matter Expert (SME) engagement. In partnership with Dr. Deena Khalil at Howard University, we are working on providing minoritized teachers and students opportunities to enhance classroom learning by relating RESOURCE mission objectives and RESOURCE science to STEM student activities.

> Prospective and practicing teachers of color learn to foster minoritized students' interest in STEM careers through direct and virtual experiences with NASA SMEs of color.

A first video featuring a NASA SME of color has been developed and will be released shortly to be shared with students through the virtual community of practice (VCoP). Initial results from this partnership were also shared as a poster at the 2020 NASA Exploration Science Forum, titled, "Resource Science Activation and Public Engagement – Partnership with Howard University." We also designed STEM resources to cultivate underrepresented students' interest in space science and aerospace careers. Resources include a Doodly video story of a Latinx SME's career path (Figure 4), infographics from the Equity, Diversity, Inclusion, Accessibility (EDIA) Planetary Science white papers, and connecting ISRU technology development with solution-prototypes that address societal programs (e.g., water "filters" can characterize the mineral potential of lunar water and help address the scarcity of clean drinking water).

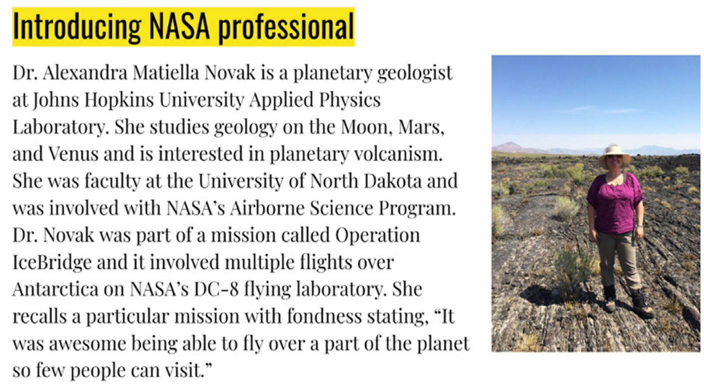


Figure 4. Portion of video story highlighting Latinx SME career path.

RESOURCE also supported two public engagement interns at JHU/APL from Howard University to develop programs to foster minoritized students' interests in STEM (Figure 5). Eman Yasin holds a BA in Biology and is currently in the Department of Curriculum and Instruction and the Teacher in Residency program for a Master's in Education. Yasin works with the National Science Teacher Association (NSTA) to advance inclusion of women in STEM, plus recruits and engages women of color SMEs to work with science activation and public engagement activities. Alvin Hannon holds a BS in elementary education and is a current teacher in Maryland. Hannon works on creating engaging resources for teachers in order to make science a more valuable asset in education.

3.2 Community Activities

RESOURCE is actively engaged with multiple NASA science activation teams. Recently, we have established relationships with the newly funded Planetary Resource and Content Heroes (ReaCH) team, which includes many scientists of color that can help with our broadening participation goals. Additionally, we have identified partnering activities with the TREX team (P.I.

Figure 5. Public Engagement interns from Howard University. Eman Yasin (left) and Alvin Hannon (right).

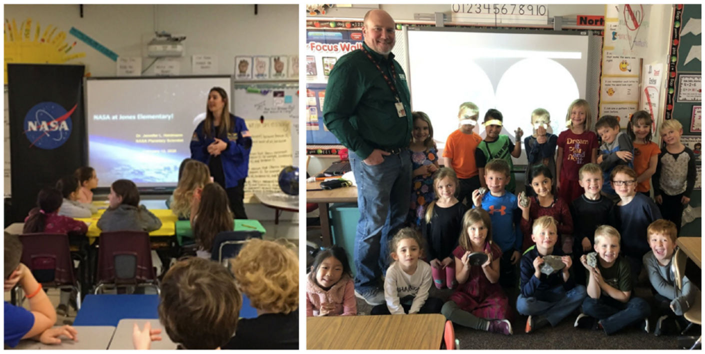


Figure 6. PI Heldmann (left) and Co-I Coyan (right) visiting elementary school classrooms (2020, pre-COVID).

Amanda Hendrix, PSI) that focus on both teams having collaborations with Howard University, and ways we can leverage and coordinate our efforts. P.I. Heldmann is a team member on the newly selected science activation team titled "NASA Community College Network" as a planetary science SME.

RESOURCE team members also regularly give talks and engage with the community at various education levels. As examples within the past year, Co-I Coyan presented a lesson on space science to a first grade class in Washington state (Figure 6). Co-I Colaprete participated in a Reddit forum answering questions regarding water on the Moon. P.I. Heldmann has presented lessons on impact cratering to fourth graders in Maryland (Figure 6), taught a class virtually at a high school in Pennsylvania, mentored a high school science teacher based in California, was featured in "Time for Kids" magazine as a space scientist, served as an SME for the Idaho Science and Aerospace Scholars program, supported interns at NASA Langley Research Center conducting a concept study for a lunar volatiles mission, and presented a public talk online via the Lunar & Planetary Institute (LPI) Cosmic Explorations seminar series titled "Roaming the Moon with VIPER."

RESOURCE team members also directly support the science and exploration communities. P.I. Heldmann served as Co-Chair and lead author for the report based on the NASA Lunar Surface Science Workshop (LSSW) focused on lunar planetary protection and PSR classification. Co-I Lim served as Co-Chair for a subsequent LSSW focused on mobility systems for lunar missions. P.I. Heldmann also serves the scientific community through service on the Mercury and Moon panel of the National Academies Decadal Survey on Planetary Science and Astrobiology, as well as serving on NASA's Artemis III Science Definition Team (SDT).

3.3 Analogs Focus Group

The SSERVI Analogs Focus Group was established by RESOURCE P.I. Heldmann, RESOURCE Co-I Lim, and RISE2 P.I. Glotch. Terrestrial analog field studies offer the unique opportunity to prepare for robotic and human planetary missions. Analogs provide the opportunity to conduct studies and tests related to science, mission operations, and technology in a relevant environment at relatively low cost and risk. The SSERVI Analogs Focus Group aims to bring together members of the community to discuss and review various aspects of fieldwork including, but not limited to, field sites, deployment logistics, field instrumentation, concepts of operations, software and hardware testing, etc. This Group currently hosts quarterly virtual seminars which are recorded and posted on the SSERVI website for later viewing. More information can be found on the SSERVI Analogs Focus Group website at https://sservi.nasa.gov/analogs-focus-group/.

4. Student/Early Career Participation

Undergraduate Students

1. Alex Forsey-Smerek, MIT Aeronautics and Astronautics
2. Trent J. Piercy, MIT Electrical Engineering and Computer Science

Graduate Students

3. Ferrous Ward, MIT Aeronautics and Astronautics
4. Cody Paige, MIT Aeronautics and Astronautics
5. Lindsay Sanneman, MIT Computer Science and Artificial Intelligence Laboratory

Postdoctoral Fellows

6. Ariel Deutsch, NASA Ames Research Center

5. Mission Involvement

1. VIPER, Jennifer Heldmann, Science Team, Mission Operations
2. VIPER, Anthony Colaprete, Project Scientist
3. VIPER, Darlene Lim, Deputy Project Scientist
4. VIPER, Matthew Deans, Robotics
5. VIPER, Ross Beyer, Ground Data Systems
6. VIPER, Joshua Coyan, Geostatistics Lead
7. VIPER, Julie Kleinhenz, ISRU
8. VIPER, Zara Mirmalek, Mission Operations
9. VIPER, Kris Zacny, TRIDENT drill P.I.
10. VIPER, CLPS, Dan Hendrickson, Astrobotic lander systems

11. VIPER, CLPS, Jennifer Lopez, Astrobotic lander systems

12. VIPER, Ariel Deutsch, Science Team

13. LRO, Dana Hurley, LRO LAMP Science Team

14. LRO, Ross Beyer, LRO LROC Science Team

15. LRO, Richard Elphic, Diviner Imaging Radiometer Team

16. LRO, Alexandra Matiella Novak, Mini-RF Science Team

17. LUNA-H Map, Anthony Colaprete, Science Team

18. KPLO, Kyeong Kim, KGRS P.I. (KPLO Gamma Ray Spectrometer)

19. CLPS / Astrobotic Peregrine Mission One, Anthony Colaprete, NIRVSS P.I.

20. CLPS / Astrobotic Peregrine Mission One, Richard Elphic, NSS P.I.

21. CLPS Astrobotic Peregrine Mission One, Janine Captain, MSolo P.I.

22. CLPS / Masten Mission One, Anthony Colaprete, NIRVSS P.I.

23. CLPS / Masten Mission One, Richard Elphic, NSS P.I.

24. CLPS / Masten Mission One, Janine Captain, MSolo P.I.

25. CLPS / PRIME-1 (Intuitive Machines Mission 2), Kris Zacny, TRIDENT drill P.I.

26. CLPS / PRIME-1 (Intuitive Machines Mission 2), Janine Captain, MSolo P.I.

27. CLPS / Firefly Aerospace, Blue Ghost lander, Kris Zacny, LISTER Co-I

28. Mars Moon eXplorer (MMX), Richard Elphic, MEGANE Gamma Ray and Neutron Spectrometer Team

29. Mars Science Laboratory (Curiosity rover), Chris McKay, Science Team

30. Mars Science Laboratory (Curiosity rover), Kris Zacny, Instrument Team

31. Mars Reconnaissance Orbiter, Alexandra Matiella Novak, CRISM Mission Operations

32. Mars 2020, Anthony Colaprete, Mastcam-Z Science Team

33. Orion spacecraft, Michael Downs, Test and Recovery Operations

34. DART, Andrew Rivkin, DART Investigation Team Lead

Mission Acronyms:

VIPER: Volatiles Investigation Polar Exploration Rover

CLPS: Commercial Lunar Payload Services

LRO: Lunar Reconnaissance Orbiter

LUNA-H Map: Lunar Polar Hydrogen Mapper

KPLO: Korea Pathfinder Lunar Orbiter

PRIME-1: Polar Resources Ice Mining Experiment-1

MMX: Mars Moon eXplorer

DART: Double Asteroid Redirection Test

6. Awards

- P.I. Heldmann, 2020 Superior Accomplishment Award, NASA Ames ODEO (Office of Diversity and Equal Opportunity) for NASA engagement with underrepresented students in STEM fields
- P.I. Heldmann, NASA / SSERVI Angioletta Coradini Mid-Career Award for significant, lasting accomplishments related to exploration
- Co-I Lim, Association of Women Geoscientists, Mavis Kent Award for Mid-Career Researchers
- Deputy P.I. Alex Sehlke, NASA Ames Honor Award, Contractor
- RESOURCE Project, NASA Ames Honor Award, Partnerships
- Co-I Dana Hurley, JHUAPL Diversity Recognition Award
- Collaborator Chris McKay, National Space Grant Distinguished Service Award
- Co-I Dava Newman, Selected as MIT Media Lab Director, effective July 2021
- Collaborator Gordon Osinski, The Meteoritical Society Barringer Award 2021

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)

Thomas Orlando

Georgia Institute of Technology, Atlanta, GA

CAN-2 TEAM

1. REVEALS Team Report

1.1 Modeling Water Formation on Mercury

Radar observations of Mercury and MESSENGER spacecraft data indicate water ice in the permanently shadowed polar regions. Generally, water delivery occurs via comets and meteoritic impacts, but researchers from REVEALS have simulated a water formation process that involves solar-wind proton implantation and OH formation in the surface of Mercury. At typical temperatures prevailing on Mercury's dayside surface, H2O can be produced from reactions involving chemically stable mineral-bound hydroxyl groups on or within the H-saturated regolith grain interfaces. This is shown schematically in the upper left quadrant of Figure 1. Thermal transformation of these hydroxyl groups (shown in green) can deliver significant amounts of H2O to permanently shadowed regions over geological time as shown in the lower portion of Figure 1. The discovery is an important but previously unnoticed source that contributes to the accumulation of water in the cold traps and polar regions of Mercury.

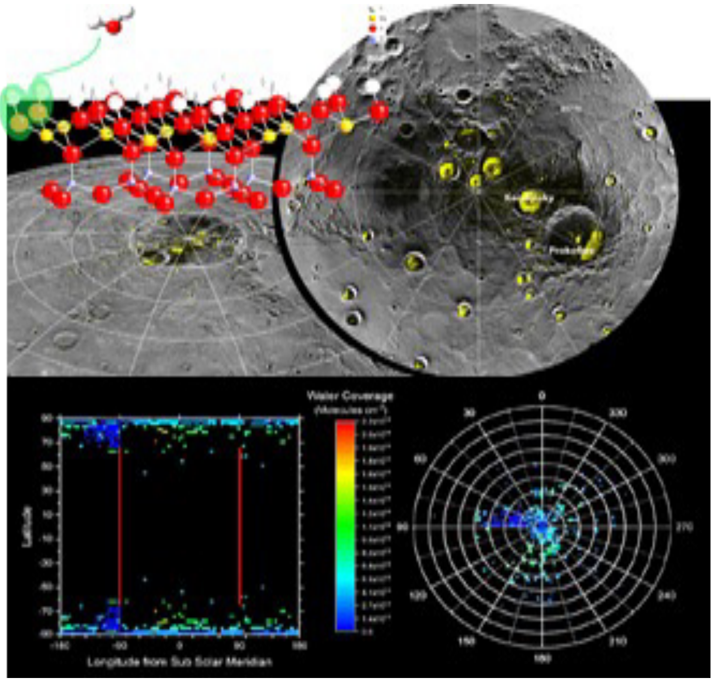


Figure 1. (Top) Yellow markings at Mercury's north pole designate permanent ice patches observed by MESSENGER. (Bottom) Graphs from the study indicate where water molecules created in the modeled chemical reaction could end up as ice on Mercury's poles.

> Forming H2O via recombinative desorption is an ubiquitous process that occurs on airless bodies such as the Moon, Mercury, asteroids and solar nebula grains that are heated above 350 K during or after proton irradiation.

1.2 Modeling and Design of ISRU Technology

To directly support NASA's planned human mission to the Moon, several Georgia Tech. projects related to understanding the formation, transport and sequestering of volatiles such as molecular water, oxygen and hydrogen were completed, resulting in design concepts for an integrated Lunar Volatile Extraction and Purification Pod (LVEPP) for in-situ resource utilization (ISRU). The proposed concept is a transportable pod structure (see Figure 2), which includes extraction, separation, and purification functions (not shown). This concept will be enabled by two major innovations to advance the capability to extract and process H2O on the Moon: (1) solar and microwave thermal extraction technology using solid, opaque pods to extract and collect H2O from lunar polar regolith; and (2) integrated passive separation and purification technologies with polymers and freeze distillation processes. With the combination of solar and microwave processes, each of which has different characteristics (e.g., depth, area coverage, etc.), the developed extraction technologies can be customized for different concentration levels and forms of H2O up to 1 meter below the surface by varying the parameters of operations (e.g., the ratio of each technology operation); this flexibility is especially beneficial because the form,

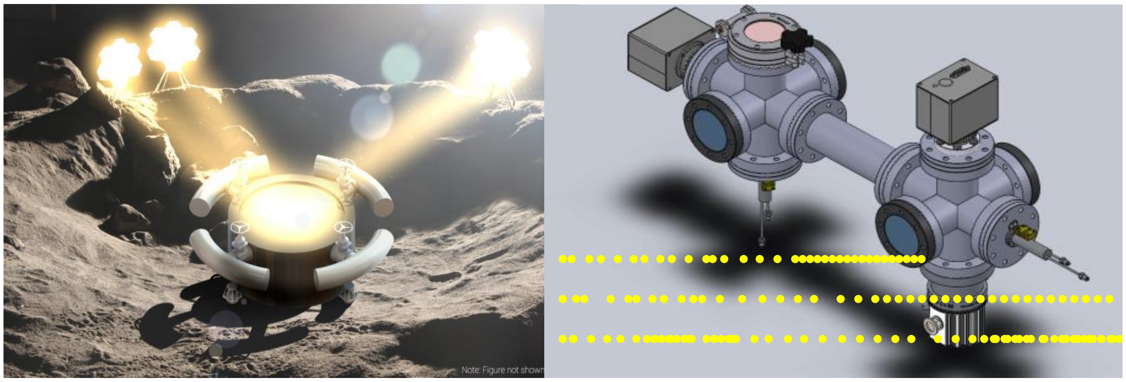


Figure 2. ISRU design concept for a Lunar Volatile Exploration Processing Pod (LVEPP). Opaque pod is mobile with support transportation system (not shown). LVEPP thermally extracts volatiles, passively "cleans" water and stores water and other useful volatiles. Left Fig. courtesy of Ms. Emily Hu.

distribution, and concentration of H2O at the lunar poles are currently unknown.

1.3 Temperature Programmed Desorption and Water Transport in Regolith

Desorption activation energies of chemisorbed water on Apollo highland sample 14163 and mare sample 10084 were determined by temperature program desorption (TPD) experiments. The TPD signal was treated as a linear combination of desorption at the grain/vacuum interface and with re-adsorption of water as it transported though the porous medium. Both samples exhibited a broad asymmetric distribution of binding site energies with sample 14163 peaking at 60 kJ mol-1, and mare sample 10084 peaking at 65 kJ mol-1. The highland sample adsorbed approximately 30% more water than the more space weathered and mature mare sample. Water desorption from the lunar surface over a typical lunar day was simulated using the extracted chemisorbed binding energies. The resulting desorption profile of water is in general agreement with Lunar Reconnaissance Orbiter (LRO) Lyman-α Mapping Project (LAMP) spacecraft-based observations assuming ~1% submonolayer coverage and that photon stimulated desorption (PSD) is neglected. Since PSD was measured to have a high cross-section, in order for water to persist at the levels reported for the LAMP data, there must be a quasi-continuous source term for migrating water. Our modeling suggests that this could be recombination desorption (RD). To address this, we carried out measurements and modeling of the thermal induced synthesis of water and evolution from simulants (expitaxial silicate films from the Univ. of Central Florida and LMS-1, LHS-1 from CLASS) and lunar regolith samples. As an example, water formation and release during heating of Apollo sample 15221 is shown in Figure 3 left frame. The results of a Monte Carlo transport model are shown in the right hand frame of Figure 3. Here water concentration is constant until the soil is warm enough to result in surface diffusion, desorption and vertical migration through the regolith. Water from RD of

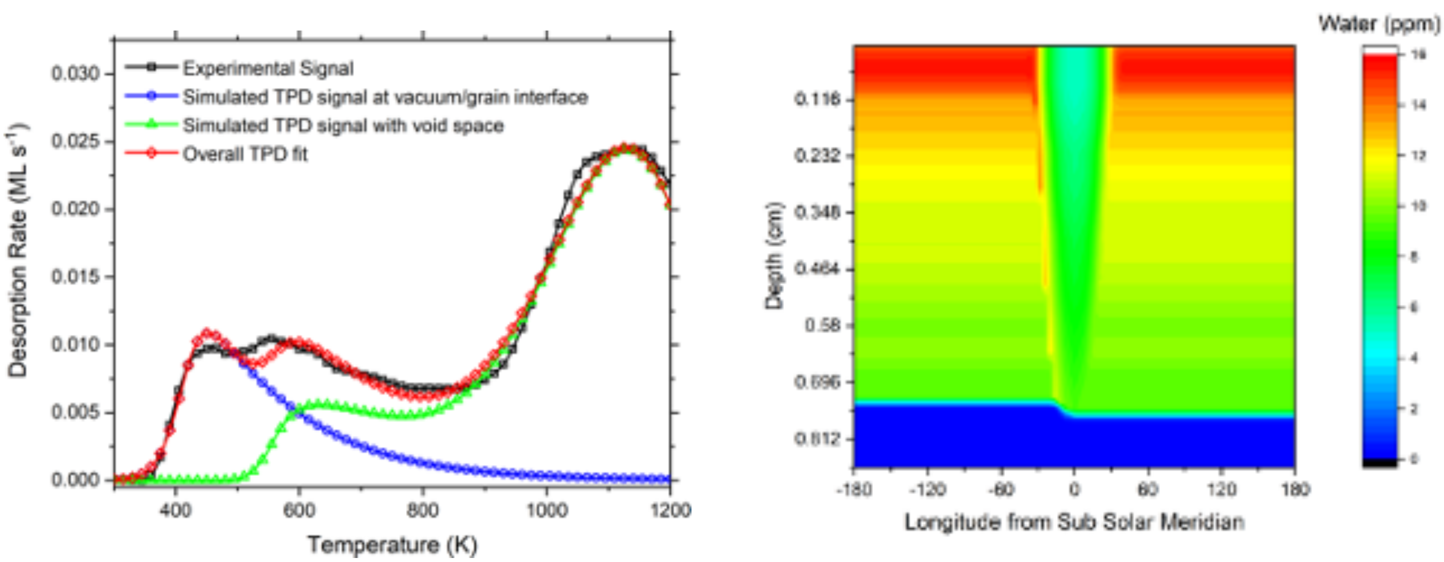


Figure 3 (Left): Left: H2O formed and released during heating of lunar highland sample 15521. The main desorption events are attributed to recombinative desorption (RD) occurring at the vacuum-grain interface yielding a peak at 450 K, RD within the pore space resulting in the broad peak centered at 570 K and sub-surface transport limited RD at 1025 K. Right: Water concentration (ppm by mass) depth profiles at 30° latitude in the lunar regolith as a function of sub solar longitude (local noon equals 0).

solar wind implanted hydroxyl defects travels downward into the regolith during the day. In the morning and dusk, the regolith temperature is warmer than the surface allowing for upward migration of water until lunar night cools the surface soil to sufficient temperatures to bind water until the next diurnal cycle.

The transport of H_2O through the lunar subsurface as it relates to ISRU was also measured and modeled using packed beds of JSC1A. Experimentation was conducted over a range of pressures from 50 to 2,065 Pa at ~350 K, corresponding to Knudsen numbers of $0.3<Kn<11$. The approach allowed for an accurate model of Knudsen diffusion and can be used to predict and model volatile transport. In addition, different models encompassing the transition regime ($0.1<Kn<10$) were evaluated. It was found that a piecewise function, with Knudsen's diffusion when $Kn>1$ and advection with slip when $Kn<1$ fit the data effectively.

This research is relevant towards sampling missions, the thermal extraction of volatiles, and ejecta/crater development caused by spacecraft launch/landing. These results are an important refinement of commonly applied transport models and will allow for increased accuracy in the design of ISRU technology.

1.4 Microparticle Impact Studies Using Laser Induced Particle Testing

Our RD measurements and modeling indicate that though RD can help explain the latitude dependence of the 2.8 micron optical measurement of the Mineral Moon Mapping spectrometer, RD is not a major source of water during a standard lunation. However, the data indicates RD can be a primary source of molecular water that results from micro-particle impact events. We have completed the construction and testing of an all-optical bench top laser induced particle impact tester (LIPIT). To date, micron sized SiO2 spherical particles (~ 4 μm) and graphite (-325 mesh) were accelerated from a launch pad to high velocities and viewed inflight and upon impact against a reduced graphene oxide polyethylene blend target material (shown in Figure 4). The launch

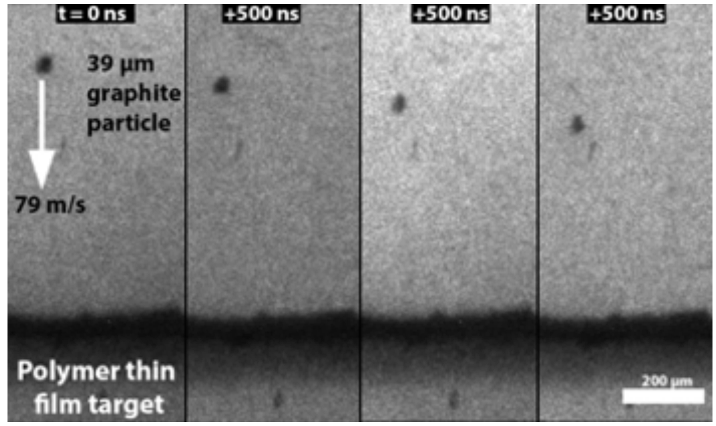


Figure 4: A 39 μm diameter graphite particle launched at a velocity of 79 m/s is captured in flight towards a thin film target material. The interframe time for each image is displayed at the top, with the first frame taken as 0 seconds. The white arrow in frame 1 shows the direction of travel of the particle.

pad (bottom) consists of a glass slide, a nanometer thick sputter coated metallic layer, and a micrometer thick polymer layer. Particles are evenly distributed on top of the polymer layer in a monolayer using a drop of ethanol. A 1064 nm Nd:YAG laser is focused on the bottom of the launch pad and with a single pulse, ablates the metallic layer and expands the polymer, accelerating the particles towards the target material. The velocities depend on the power density with expected velocities of up to a few km/sec. The initial impact studies will focus on polymer composites being developed by REVEALS team members for radiation protection, dust mitigation and other EVA and spacesuit applications.

The initial impact studies will focus on polymer composites being developed by REVEALS team members for radiation protection, dust mitigation and other EVA and spacesuit applications.

1.5 Synthesis and Characterization of Electrically Conductive Polymer Composites

A goal of the composites program is to develop electrically conducting polymer-based materials that address the needs of future space missions and human habitation. Central to these efforts has been the modification of reduced graphene oxide (rGO), a synthetic treatment that enables scalable processing. Our efforts have pursued two preparation strategies: melt compounding and melt

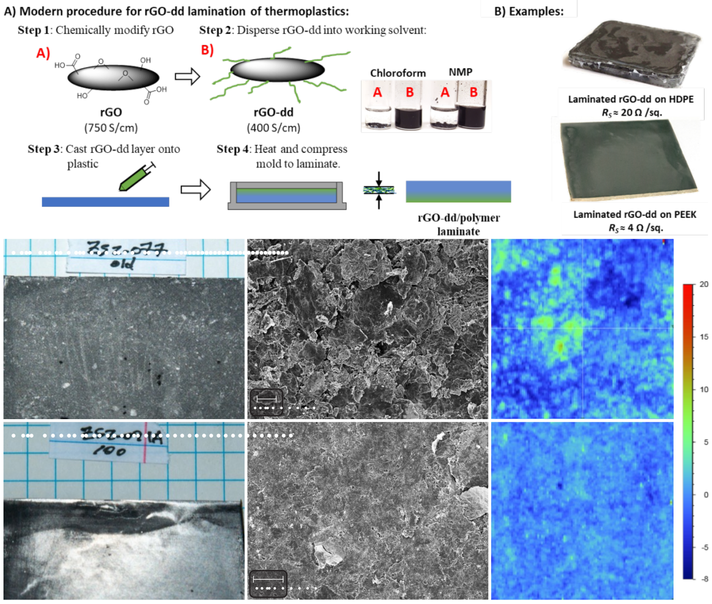


Figure 5. A) Schematic for rGO-dd modification lamination of thermoplastic materials. B) rGO-dd laminates for HDPE using a molding method compared to a laminated PEEK substrate. Rows C & D are different versions of rGO-dd laminate layers deposited along with corresponding optical images (left), scanning electron micrographs (middle), and profilometry scans (right).

lamination. The melt lamination schematic is shown in Figure 5A. Recent work has focused on smoothing the topography at the micron scale while minimizing the sheet resistance. Our efforts culminated in smooth surfaces with sheet resistances consistently around 10 Ω/□. These sheet resistances are sufficient to dissipate static charge providing a potential path for dust mitigation. REVEALS team members are characterizing the molecular interactions between surfaces and dust, optimizing measurements on surfaces covered in regolith, and designing lunar dust mitigation techniques for sustained human presence and operations on the surface of the Moon.

REVEALS team members are characterizing the molecular interactions between surfaces and dust, optimizing measurements on surfaces covered in regolith, and designing lunar dust mitigation techniques for sustained human presence and operations on the surface of the Moon.

1.6 EVA Radiation Protection

A project on radiation protection involving the "SpaceVEST" and "SpaceRADCAP" activity at Florida Space Institute and the University of Central Florida focuses on the development of 3D printed vests and skullcaps that optimize crew safety during EVA activities. The project incorporates a layered approach to the spacesuit design in order to combine radiation protection and thermoregulation to crew. Radiation damage studies on the 3D printing polymers as well as the rGO composites from GT have also begun at the US Dept. of Energy supported radiation laboratory at the University of Notre Dame.

Figure 6: 3D-printed prototype design, cooling garment, and headpiece with tubing that will be used to incorporate our prototype with a layered approach for "SpaceVEST and SpaceRADCAP."

1.7 Two-dimnesional Materials Approach for Radiation Detection

Graphene FET as a neutron dosimeter. We have used the graphene field-effect transistor (gFET) as a test platform for evaluating material properties under radiation exposure and to determine optimal combinations to create radiation-sensitive metamaterials. Using CVD graphene transfer, electron beam lithography, and various clean room methods, two neutron-series (n-) prototypes have successfully reached the terminal step of development.

Organic two-dimensional materials for space applications. Team members investigated 2D covalent organic frameworks (2D-COFs) for potential applications as flexible semiconductor devices, flexible conductive materials for spacesuits, electronic radiation sensors, and membranes for low-energy chemical separations. From the perspective of electrical devices, a main attraction of 2D-COFs is the potential to design their electronic structure through appropriate choices of precursor monomers and linker molecules. Synthesis can be done chemically (a synthetic route different from other 2D materials), but our initial investigations of electronic properties use small 2D-COF arrays synthesized on silver or gold surfaces in vacuum, where advanced techniques for both physical and electronic structure analysis can be applied.

1.8 Helmet Mounted Display

REVEALS is investigating the integration of active dosimetry for EVA and surface exploration concepts. A helmet-mounted display enables real-time dosimetry data to be available to crewmembers during EVAs and planetary surface operations. Real-time radiation levels will be measured from multiple dosimeters (also developed by the REVEALS team) on the spacesuit, and the user display will show both the current and cumulative radiation dosage levels upon user prompting. To test a helmet-mounted display in an operationally relevant environment, the UC Davis REVEALS team members partnered with the NASA JSC Human Physiology, Performance, Protection, and Operations (H-3PO) Lab. The team is creating and testing HMD prototypes for underwater EVA training in JSC's Neutral Buoyancy Laboratory (NBL). The helmet-mounted display prototype is low-cost, low-tech, and follows an accelerated timeline—from initial concept to engineering evaluations during NBL EVA training in one year. Extensive subsystem testing and iterations were performed prior to underwater testing and integration with NBL training.

> Developing new materials that are mechanically strong, resistant to dust, conductive and stable to radiation is necessary for long term exploration of Humans on the lunar surface. In addition, real time data display and passive measurements of radiation exposure can help realize and mitigate risk during EVA and lunar surface operations.

2. Inter-team/International Collaborations

CLASS Collaborations: Regolith Shielding, Volatile Transport and Dust Mitigation: Collaborations with Dan Britt (UCF) continue on understanding the thermal production and release of water and other volatiles from asteroid simulants developed in the EXOLITH lab. These simulants are now being used by REVEALS team (Schieber, Clendenen, Jones and Loutzenhiser) in measurements of diffusion and transport coefficients of volatiles such as Ar and water in regolith. Kaden's team (UCF) has also collaborated with the CLASS team to select mineral-based simulants currently being investigated as an extension of the group's thin-film study. D. Britt (CLASS-P.I.) is also a member of the REVEALS advisory board.

VORTICES Collaborations: Temperature Programmed Desorption and Formation of Water from Regolith: Collaborations with Hibbitts (VORTICES) and Dyar (VORTICES) on understanding the kinetics and mechanisms of temperature-induced release and formation of molecular water from lunar regolith and surface material continue. The team demonstrated the importance of solar wind induced hydroxylation and recombinative desorption in forming water at temperatures above 350K. Jones has recently expanded this effort to look at sub-surface transport.

LEADER and IMPACT Collaborations: Health Effects of Charged Dust Grains: Dr. Micah Schiable, a NASA Program Postdoctoral Fellow, is working with IMPACT and LEADER in developing an apparatus and testing protocol to examine the effects of grain charging on health. Specifically, the program mainly examines the interaction of charged grains with surrogate lung membrane surfactants. The program is generally geared towards understanding and controlling grain charging effects on chemistry. It will continue with future support for Schiable involving LEADER. Note William Farrell (DREAM2-P.I. and LEADER Co-I) is also a member of the REVEALS advisory board.

TREX Collaborations: LRO LAMP VUV Spectroscopy: Hibbitts and Cahill (REVEALS team members at JHU/APL) have been working with the TREX SSERVI team, providing UV spectra to aid their investigations into the nature of LRO LAMP data. The APL group has also concurrently collected Vis-IR (8000 nm) spectra of the samples in conjunction with the UV data. They are exploring correlations between UV signatures and IR signatures in an attempt to better understand the similarities and discrepancies in the LRO LAMP and IR observations. Bennett (REVEALS and CLASS) has also been working with TREX and the University of Lille to build a space weathering chamber to study the effects of UV photons and keV electrons on surfaces. These surfaces will be analyzed using transmission electron microscopy with energy dispersive X-ray spectroscopy.

ICE-FIVE-O: Orlando and Hibbitts helped assess the amount of chemisorbed water on the Moon with respect to the observations of the 6-micron feature using SOFIA. This involved collaboration with ICE-FIVE-O member Lucey.

3. Public Engagement Report

Education and public outreach activities take many forms across the REVEALS team, and are integral to our core values. Educational opportunities seek to engage students at many different stages of their educational career and provide them training and inspiration in the STEM fields, while Public Engagement activities seek to expose the greatest number of people to the awe, excitement, and inspiration that comes through space exploration and technology development. While the Covid-19 landscape has limited in-person engagements, the REVEALS team has developed and/or participated in several virtual public outreach activities, highlighted in three categories below.

Summer Camps (Virtual): 'Truss Me' & FMS Research Explorers (6/29 – 7/9/2020)

Investigator Rimoli developed a virtual 3-day summer camp 'Truss Me' targeted at early high school students from several under-represented minority serving schools in the Atlanta area. The main goal was to introduce basic physics, materials science, and structural engineering concepts using an application that realistically calculates material properties of student-designed structures in a gaming environment. Students also gained professional development experience in presenting their research projects at the end of the camp. The 'Truss Me' program was also incorporated into the Freedom Middle School Research Explorers summer camp led by Investigator Kabwatha, adding a rich exposure to university research to many under-represented middle school students.

Virtual Public Outreach and Engagement

From virtual hackathons, to broadcast television interviews, science advertisements during football games, to STEM Connect virtual class visits, the REVEALS team interacted with literally millions!

i. Broadcast Research Collaboration During Notre Dame-Clemson Football Game (11/7/202)

REVEALS Research Collaboration video broadcast to over 10 million viewers with two minutes of interviews with Investigators LaVerne, Robinson, and Orlando.

https://fightingfor.nd.edu/2020/fighting-to-reach-the-next-frontier-in-space/

ii. NASA COVID-19 SpaceApps Hackathon (May 30-31, 2020)

Investigator Beltran served as subject matter expert in Medicine for the COVID-19 United Nations Sustainable Development Goals group. Thousands of participants formed teams from around the world.

https://covid19.spaceappschallenge.org/

iii. Investigator Beltran Interviewed by Telemundo for SpaceX Commercial Crew Launch

iv. Investigator Beltran Served as a judge for the Astronaut Scholarship Awards

v. Investigator Paty presented at the virtual American Geophysical Union meeting (12/10/2020)

Education Section talk on a new pedagogy for 'Training the Next Generation of Public Science Writers.'

Museum Installation Project: Aerospace Museum of California (Sacramento)

Investigator Robinson has partnered with the Aerospace Museum of California to design and install a "Space for You" exhibit. This project has reached a critical phase over the last year; UC Davis Design Graduate Student Tracy Corado finalized the design informed by research to engage underrepresented audiences in STEM exhibitions, and obtained cost estimates from exhibit fabricators. The project has a modular and updatable design, with a narrative developed around five subjects: 1) How We Travel- which introduces space vehicles and tourism 2) Where We Live- long term space exploration requirements 3) What We Wear- material science and wearable technology 4) What We Eat- agriculture and nutrition 5) What We Build- robotics and technology. These familiar topics were selected to introduce more complicated subjects through everyday situations, making them more approachable for children, specifically girls, who are an underrepresented group in STEM. Once a design firm is selected, designs will be finalized and fabrication will begin.

Figure 7: Interactive elements, such as videos triggered by sensors, encourage learning through play.

4. Student/Early Career Participation

Undergraduate Students

1. Ruby Houchens, UC Davis Ruby Houchens, UC Davis, worked to help decrease astronaut motion sickness during gravitational transitions.

2. Steven Licciardello, Georgia Institute of Technology, Physics, laboratory assistant working on gFET.

3. Gloria Jillian, UCF, Instrument development (student has taken on additional project within CLASS' Exolith Lab).

4. Riley Havel, University of Central Florida, Specialty: Diffuse reflection spectroscopy, ab initio calculations, hydration levels of the Martian surface.

5. Sarah Swiersz, University of Central Florida, Specialty: Space Policy, ab initio calculations.

6. Halle Helfrich, Pittsburg State University, Physics, [CANCELLED due to Covid-19].

7. Makayla Sisson, Atlanta Public High-School student, research experience/project supervised by GT investigators Jiang and First.

Graduate Students

1. Janine Moses, UC Davis, worked on EVA-Helmet display technology.

2. Tracy Corado, UC Davis, worked on "Space for You" museum display.

3. Elliot Frey, Georgia Institute of Technology, Chemistry, involved in developing gFET radiation sensors (full support).

4. Faris Almatouq, Georgia Institute of Technology, Physics, involved in developing gFET radiation sensors (fellowship support).

5. Zachery Enderson, Georgia Institute of Technology, Physics, 2D COF materials (partial support).

6. Alisha Vira, Georgia Institute of Technology, Physics, worked on new materials (separate support).

7. Garrett Schieber Georgia Institute of Technology, Mechanical Engineering, Ph.D. thesis work on experimental and theoretical studies of volatile transport and ISRU (full support). Garrett has accepted a postdoctoral appointment with CLASS and will be jointly mentored with REVEALS for further career advancement in the area of ISRU.

8. Ashley Clennenden, Georgia Institute of Technology, Mechanical Engineering, solar technology based volatile production and ISRU (full support). Graduated in August 2020 with a MSc in Mechanical Engineering. Currently a Ph.D. student in the GT School of Physics.

9. Bijoya, Dhar, University of Central Florida, Ph.D. thesis work on thin-film simulant research and development (full support).

10. Amy, LeBleu-DeBartola, University of Central Florida, Specialty: thesis work on Raman spectroscopy, space weathering, meteorites and space policy (partial support).

11. Katerina, Slavicinska, University of Central Florida, Specialty: thesis work on space weathering, diffuse reflection spectroscopy and meteorites (partial support).

Postdoctoral Fellows

1. Micah Schiable, NPP Fellow. The interaction of charged dust grains with materials and biological interfaces.

New Faculty Members

1. Melodie Yashar UC-Davis, Modeling radiation damage and energy deposition in materials.

Research Experience for Undergraduates

5. Mission Involvement

- SSERVI GT Co-Is Orlando, Loutsenhizer, and Jones teamed with investigators at the Colorado School of Mines, CLASS, TransAstra, Paragon and Pioneer Astronautics, to develop a novel lunar ISRU paradigm that involved solar and microwave extraction and passive purification of volatiles from the polar and near polar regions. The concept and team effort proposed to the NASA LUSTR program was based on both modeling and experimental efforts initiated and funded by SSERVI.
- Siebers (GT) and Orlando (GT) provided extensive consultation for GT student-led teams competing in the NASA 2021 "Breakthrough Innovative and Game-changing (BIG) Idea Challenge" focusing on lunar dust mitigation strategies. These efforts culminated in two submitted proposals titled "Hybrid Dust Mitigation Brush Utilizing EDS and UV Technologies" and "Soteria." Soteria is focused on mitigating dust during landing.
- JUICE, Particle Environment Package (PEP), Carol Paty, Co-Investigator. The SSERVI work on solar wind plasma fluxes is relevant to Paty's efforts on the PEP package.
- Europa Clipper, the MISE instrument team, Karl Hibbitts. The SSERVI work on lunar polar regions is

relevant to Hibitt's efforts on Europa ice and non-ice material.

- Europa Clipper, Plasma Instrument for Magnetic Sounding (PIMS) and the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON), Carol Paty, Co-Investigator. The SSERVI work on plasma interactions and ice signatures is relevant to Paty's efforts on PIMS and REASON.
- Paty is serving on a National Academies panel for the Planetary Science and Astrobiology Decadal Survey 2023-2032.

https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

6. Awards

- Thom Orlando (GT-Faculty), Received the Theodore Madey Award from the American Vacuum Society for his contributions of applying surface chemistry and physics to problems in planetary science.
- Bijoya Dhar (UCF Graduate Student; Kaden) was awarded UCF's Graduate Thesis Completion Fellowship, which will allow her to finish some ongoing work related to her SSERVI project in Spring 2021.
- Carol Paty received a University of Oregon Fund for Faculty Excellence award in Fall, 2021.

Remote, In-Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2)

Timothy Glotch
Stony Brook University, Stony Brook, NY

CAN-3 TEAM

1. RISE2 Team Report

The RISE2 team is organized into four distinct themes, which in addition to our Public Engagement efforts, form the core of our science and exploration efforts. Results from the first year of RISE2 activities for each of the four themes are discussed below.

1.1. Theme 1: Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies

In Year 1, the RISE2 Theme 1 team made substantial progress towards our goals. Our work has focused on continued application of simulated airless body environment (SAE) spectroscopy for direct comparison between laboratory thermal infrared (TIR) spectra and remote sensing data from the Moon and asteroids and near-field infrared (nano-IR) model development and data acquisition for ordinary and carbonaceous chondrites.

1.1.1. Simulated Asteroid Environment Spectroscopy

Our work in Year 1 occurred in coordination with P.I. Glotch's role as a Participating Scientist Co-I on the OSIRIS-REx team. Stony Brook University graduate student Laura Breitenfeld has prepared and acquired SAE spectra of over 150 mineral mixtures designed to cover the range of compositions reported in CI and CM carbonaceous chondrite meteorites. These spectra form the basis of a training set for a partial least squares (PLS) multivariate model to determine the composition of the asteroid Bennu from OSIRIS-REx Thermal Emission Spectrometer (OTES) infrared spectra. To test the effectiveness of the model Breitenfeld also acquired spectra of CI and CM chondrites including Murchison, Essebi, Orguiel, ALH 83100, ALH 81002, MET 01070, QUE 93005, QUE 97990, and SCO 06043. Each of these meteorites have had quantitative modal mineralogy determined by powder X-ray diffraction (XRD) measurements. This allows us to compare the model mineralogy results of the PLS model to those from XRD and provide error estimates for our analyses of OSIRIS-REx OTES data. This work is being supported by Co-I Ebel and Columbia graduate student Marina Gemma. Model development is still occurring, but our initial results show that the model can accurately predict phyllosilicate abundance in meteorites, although it sometimes over- or under-estimates abundances. It also accurately predicts pyroxene, magnetite, and carbonate abundance. However, the model greatly overestimates olivine abundance. We are completing further work on the model and adding new spectra to the training set, which we hope will reduce the model error.

1.1.2. Near-field Infrared (nano-IR) Spectroscopy and Model Development

Co-I Mengkun Liu and postdoctoral researcher Xinzhong Chen have been working in Year 1 to refine models of the near-field interaction of sample surfaces and the nano-IR atomic force microscope (AFM) probe tip that enables infrared measurements at 20 nanometer spatial scales. Due to the strong electromagnetic interaction between the AFM tip and sample surface, nano-IR spectra are typically distorted and shifted compared to their traditional far field reflectance or absorbance counterparts. A major goal of our work is to increase the fidelity of models that are used to calculate mineral optical constants from nano-IR data so that nano-IR measurements of returned samples can be directly compared with infrared remote sensing measurements of sample parent bodies.

In addition to model development we acquired substantial nano-IR data through remote sessions at the Lawrence Berkeley National Laboratory Advance Light Source. Our efforts focused on the CM2 chondrite ALH 83100 which is likely a good analog material for the samples returned from the Hayabusa2 and OSIRIS-REx missions. Using lasers available at the ALS, we acquired multiple images at wavelengths between ~10.5 and 6 microns. Using standard remote sensing multispectral data visualization methods, we have produced false color images like that shown in Figure 1 to aid in compositional analysis of the samples and guide our further data collection for individual hyperspectral nano-IR spectra. These data

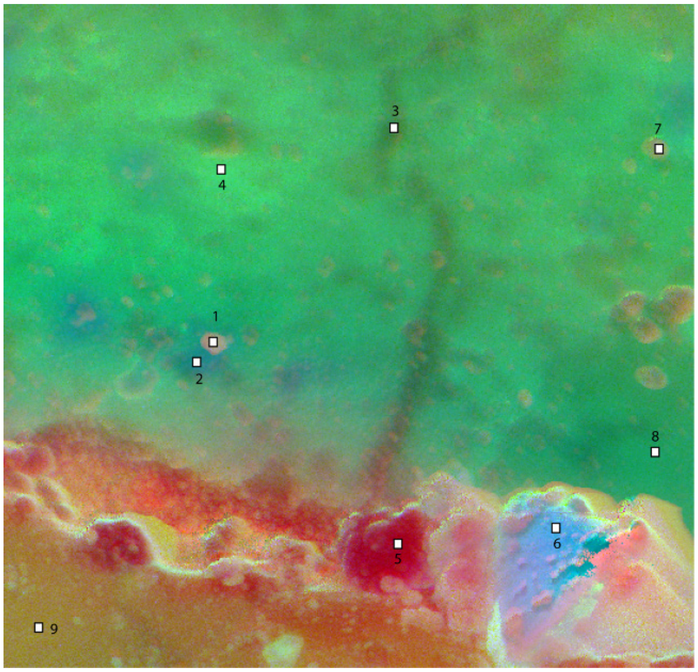


Figure 1. False color RGB image composite of a chondrule-matrix boundary in CM2 chondrite ALH 83100. R, G, and B color channels represent the 10.59, 9.62, and 9.25 μm wavelengths, respectively. Black-edged squares represent positions where single spectra were collected. The image is 11 μm across with 20 nm/pixel spatial resolution.

demonstrate sub-micron compositional variability in the sample matrix and chondrule rim, pointing to complex, likely non-equilibrium aqueous alteration processes on the meteorite parent body.

The nano-IR data that we collected during Year 1 of our work were used to demonstrate the method in a recently funded NASA Laboratory Analysis of Returned Samples proposal with Glotch as the P.I.. The funded LARS work will enable us to purchase a nano-IR system capable of hyperspectral imaging at 20 nanometer spatial scales, and perform coordinated analyses with synchrotron X-ray measurements of light elements and scanning transmission electron measurements of the same samples.

1.2. Theme 2: Maximizing Exploration Opportunities: Development of Scientific Field Methods for Human Exploration

Despite changes made to the RISE2 Theme 2 Year 1 proposed plan due to the COVID-19 pandemic, we made significant progress to our theme goals in several key areas. While some RISE2 Theme 2 team members were part of the original RIS4E team, others were not. We conducted a series of virtual meetings early in the year summarizing data collected and field strategies developed during RIS4E funding, as well as identifying gaps in those data to tackle in RISE2 work.

1.2.1. Distinguishing Volcanic Events with Portable Instruments

To unravel the eruptive history of the Kilbourne Hole (KH) volcanic structure, and therefore evaluate a surface analysis strategy for lunar explosive basaltic deposits, we will collect and analyze portable instrument data, develop new strategies for analysis of RIS4E data, and subsequently complete lab analysis of collected data. To begin the process of developing the instrument suite to tackle these science questions, processing and integration methods are under development (Figure 2) for data acquired by the handheld laser induced breakdown spectroscopy (LIBS) and handheld X-ray fluorescence (XRF) instruments with the ultimate goals of interrogating KH's eruptive history, generating near-instantaneous summary data products for integration into EVA visualization software, and detailed analysis products for post-EVA and/or ground-based assessments.

1.2.2. Defining Exploration Protocols and Con Ops

Although we were not able to complete fieldwork in Project Year 1, we did begin this task work by discussing exploration strategies with our instrument teams. Based on lessons learned from RIS4E, as well as a broad experience base with our team members, we started to develop instrument operational strategies to test once fieldwork resumes. Especially important in these discussions were a) taking inventory of field instruments and capabilities across the team and b) developing a strategy for deployment of the numerous uncrewed aerial vehicles (UAVs) on the team (led by UAV lead S. Scheidt).

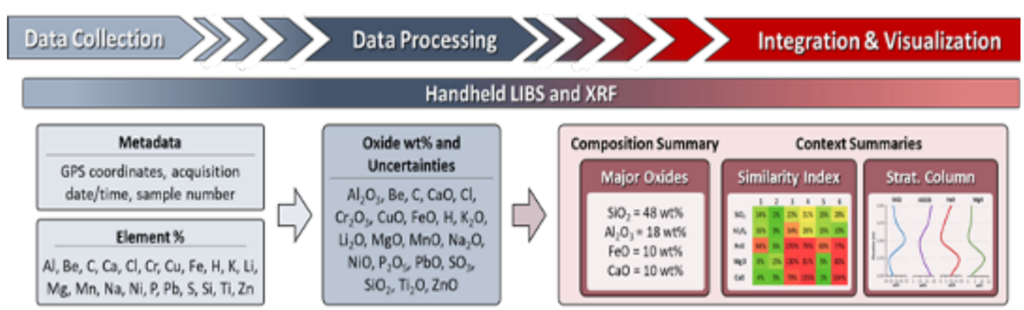


Figure 2: Data processing flow (lead: RISE2 postdoc C. Achilles) being developed for RISE2 science objectives.

1.2.3 Data Processing, Assimilation, Visualization, and Management

Per our Task 3 goals, we are developing several software tools capable of developing and evaluating concepts for how to process and visualize high volume science instrument data sets real-time during surface exploration. We are evaluating and developing several concepts, including software (leads: B. Feist and C. Pittman) to integrate data, an Augmented Reality (AR) phone app to aid in geologic fieldwork and exploration (lead: RISE2 postdoc Z. Morse, Figure 3), and a partnership with U. of Western Ontario (lead: G. Osinski) to field test a phone app for geologic fieldwork developed at UWO.

Figure 3: Early stages of AR app development (left: photo of a rock wall; right: AR data overlay). Right image shows potential of being able to display instrument data in the AR app.

1.3. Theme 3: Protecting our Explorers: Understanding How Exposure to Lunar and Asteroid Regolith Impacts Human Health

In our first year, we made significant progress towards our goals, including materials synthesis and reactivity and toxological studies of lunar regolith simulants.

1.3.1. Method Development and Synthesis of Lunar Regolith Analog Materials

Our program of research begins with the acquisition and/or synthesis of high-fidelity regolith simulants, and their characterization, so that they can be used in subsequent reactivity and toxicological studies. We have designed experimental methods to simulate space weathering through high temperature roasting in an H2 gas stream. We have subjected olivine mineral and three regolith simulants to this treatment and observed the production of nanophase metallic iron on particle surfaces (Figure 4). We have built and calibrated a furnace for lunar magma degassing experiments to simulate the generation of vapor phase deposits enriched in volatile, toxic compounds. We have generated a simulant of the Apollo 74220 orange glass with and without volatile components, which will be subjected to volatile phase degassing experiments in the degassing furnace. Following characterization, these volatile-enriched simulants will be made available for reactivity and toxicity experiments. Finally, we have synthesized a number of single mineral phases under low oxygen fugacity for use in a range of RISE2 projects.

1.3.2. Lunar Regolith Analog Reactivity and Toxicity

In Year 1, our work on the reactivity and toxicity of regolith simulants has involved synthetic and natural minerals, the JSC-1A lunar regolith simulant, and the SSERVI CLASS team's Exolith Lab LMS-1 and LHS-1 simulants. Figure 4 shows that all the experimentally space weathered regolith simulants exhibit an increased capacity to generate reactive oxygen species (ROS) in solution relative to their unweathered counterparts. In collaboration with members of the SSERVI REVEALS team, we are working towards a mechanistic understanding of why ROS are generated by freshly pulverized minerals, focusing on attenuated total reflectance Fourier transform infrared (ATR-FTIR) measurements of the surface properties of synthesized olivines across the entire solid solution series.

We are making significant progress in our toxicological studies, including the development of new assays for detecting DNA damage in cell nuclei and assessing mitochondrial dysfunction following exposure to regolith simulant materials. We have developed simple methods to process images of cells incubated with regolith by removal of regolith particulates from the background incubation medium. We also received approval by the Institutional Animal Care and Use Committee (IACUC), which is required for tracheal instillation as an initial whole animal (mouse)

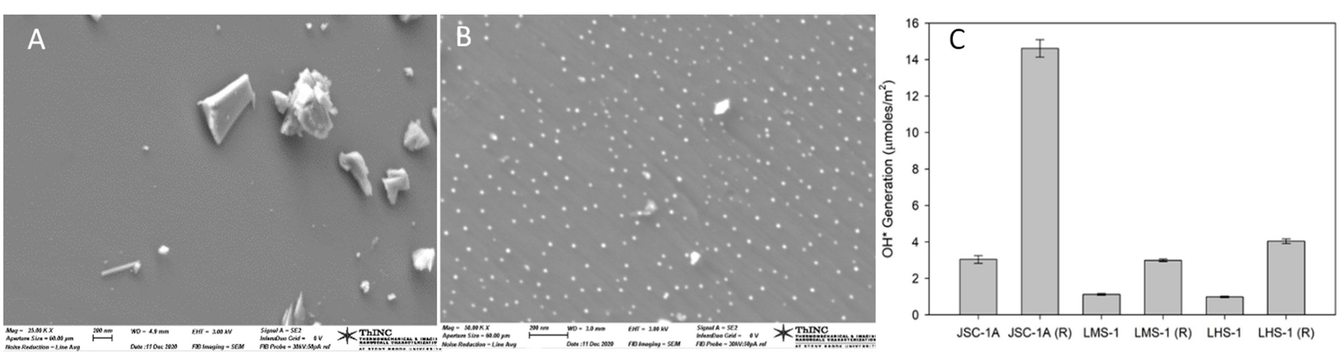


Figure 4: (A) SEM image of untreated olivine and (B) olivine after experimental space weathering, showing the formation of metallic iron globules at the mineral surface. (C) Hydroxyl radical generation by simulants before and after experimental space weathering treatment (designated by (R)).

exposure to the simulants, as we anticipate the purchase, installation, and new experiments on laboratory mice using a dust inhalation chamber in FY22.

In 2020, we submitted a review paper on the effect of regolith on different organs (see below). We have given 7 presentations of our work: at the LPI-sponsored Lunar Dust Forum (2), the NASA Lunar Science Forum (2), the AGU Fall Meeting (2), and the Stony Brook Univ. Undergraduate Res. & Creative Act. meeting (1). Our work at the Lunar Dust Forum featured prominently in the recently published workshop report entitled "Lunar Dust and its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop."

1.4. Theme 4: Maximizing Science from Returned Samples: Advanced Synchrotron and STEM Analysis of Lunar and Primitive Materials

The Theme 4 team is dedicated to developing and applying new technologies for analysis of returned samples using microbeam methods.

1.4.1. Microscale X-ray Absorption Fine Structure Analysis of Valence States

Despite the shutdown of the Advanced Photon Source in March of 2020, we have implemented and tested the high energy-resolution fluorescence detection XAFS (HERFD-XAFS, ≤ 1 eV) system at beamline 13-ID-E, led by Co-I's Tony Lanzirotti, Steve Sutton, and Darby Dyar, as well as GSECARS beamline scientist Matt Newville. This HERFD-XAFS system required design and installation of crystal analyzer spectrometers for measuring the fluorescence XAFS rather than the energy dispersive solid-state detectors typically used (~130 eV resolution). We acquired test data on a synthetic basaltic glass standard and on Apollo lunar glass beads and began development of new calibration models using HERFD-XAFS for very low abundance, multivalent element oxybarometers such as Eu. Figure 4 shows preliminary results collected on a glass standard and demonstrates that Eu HERFD-XAFS at 1 ppm concentrations (or lower) is clearly feasible.

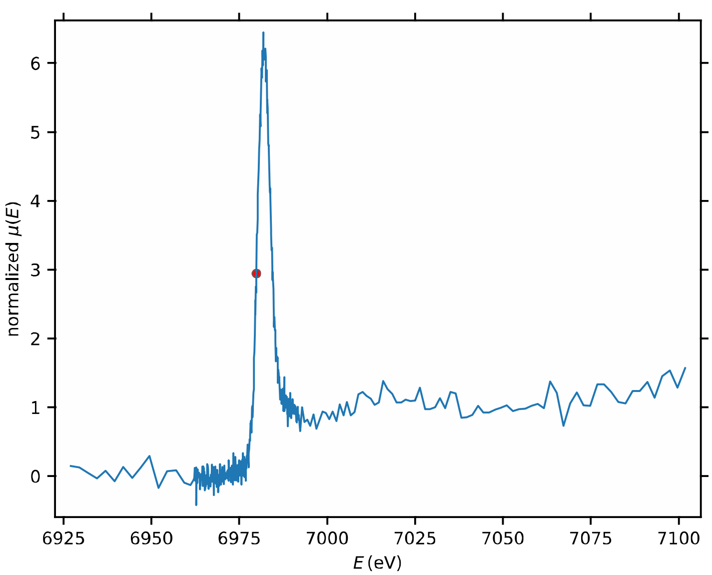


Figure 5. Eu Lα HERFD XAFS collected on GSA-1G (merge of 55 repeat spectra) showing a good quality Eu^{3+}-dominated spectrum.

1.4.2. Space Weathering, Coatings, and Impact Effects

Co-I Burgess studied three regolith grains from asteroid Itokawa, collected by the first Hayabusa mission. Each shows space weathering consistent with what others have observed on Itokawa particles, as well as evidence of oxidation within weathering rims and volatiles retained in vesicles.

1.4.3. Advanced XAS and STEM Measurements of Returned Samples

Co-Is Stroud and De Gregorio have developed sample preparation and analysis protocols for working with regolith particles using crushed particles of carbonaceous chondrite meteorite Jbilet Winselwan (CM2). This meteorite was selected by the Hayabusa 2 Organics Sub-Team as a potential analog for the C-type asteroid Ryugu (the target of Hayabusa 2 sample collection) to match the low levels of shock heating inferred from remote sensing of the Ryugu surface.

Because relatively large (~1 mm) particles of Ryugu were collected by Hayabusa 2, Co-I De Gregorio continued development of a new procedure for extracting sub-samples of large particles using FIB-SEM for subsequent sulfur-embedding and ultramicrotomy, which allows for correlated analysis of a wide variety of techniques. The latest version of this protocol in October 2020 was successful and produced STXM X-ray absorption near-edge structure (XANES) spectra consistent across all samples and consistent with slightly heated insoluble organic matter. Co-I Stroud also collected several long-dwell-time STEM-EELS-EDS datasets from Murchison IOM under various experimental conditions to develop measurement protocols for future asteroid sample analysis that will maximize data quality while minimizing potential beam damage of organic matter.

Co-I Stroud also performed cutting-edge nm-scale vibrational spectroscopy using the aberration-corrected, monochromated Nion STEM at Rutgers University with Collaborator Philip Batson on sub-μm SiC polytype grains with different crystalline ordering. With collaborator Beth Hudak, Stroud also investigated the nature of chondritic nanodiamonds.

2. Inter-team/International Collaborations

The RISE2 team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our Experiences have provided evidence that the whole of SSERVI is greater than the sum of its parts.

2.1. Inter-team Collaborations

2.1.1. Collaboration with the GEODES Team

Although field work was canceled due to the COVID-19 pandemic in 2020, the RISE2 team had planned to include members of the GEODES team during fieldwork in the Potrillo Volcanic Field in New Mexico in spring of 2020. The goal of this GEODES collaboration was to conduct a 2-D seismic, gravity, GPR, and magnetic profile of the Kilbourne Hole Volcanic Crater to determine the nature of the subsurface dike that supplied the eruption with magma. The survey would be designed to be analogous to a similar survey on the Moon, and serve as an opportunity to familiarize astronauts and participants with geophysical equipment and active sounding techniques. Once travel becomes available to the teams, GEODES and RISE2 will rekindle this new inter-team partnership and collaboration.

2.1.2. Collaboration with the RESOURCES Team

P.I. Glotch continued work with Resources P.I. Jennifer Heldmann and Darlene Lim to operate the SSERVI Analogs Focus group. This group now has over 100 members on its email distribution list. It hosts focus group meetings at the annual NASA Exploration Science Forum and, with the support of SSERVI Central's technical staff, runs quarterly seminars related to analog activities. These seminars are recorded and available for playback by any member of the public or scientific community.

2.1.3. Other Collaborations

We have been working with REVEALS team members to better understand the surface chemistry of pulverized and weathered minerals to better link minerals surface speciation to reactivity and chemistry. We have also begun work with the ICE-FIVE-O team, who will experimentally space weather lunar simulants using nanosecond pulse lasers and provide the materials to us for reactivity and toxicity analyses.

2.2. International Collaborations

Drs. Gordon Osinski (University of Western Ontario) and Ed Cloutis (University of Winnipeg) are RISE2 collaborators. Osinski is the P.I. and Cloutis is a team member of the Canadian Lunar Research Network (CLRN), providing a link between the two teams. Osinski will be a key collaborator on RISE2 Theme 2 field work and Cloutis continues to collaborate with RISE2 Theme 1 team members on infrared spectroscopy of extraterrestrial and terrestrial analog materials. Osinski and Cloutis will each host (in person or virtually) undergraduate researchers funded by the RISE2 team during the summer of 2021.

Dr. Mehmet Yesiltas from Kirklareli University (Turkey) is now a RISE2 collaborator, working with P.I. Glotch and SBU graduate student Jordan Young on Raman spectroscopic measurements of ordinary and carbonaceous chondrites. He is a co-author on a paper by Young currently in review in Meteoritics & Planetary Science, and a lead author on a paper with Young and Glotch that has been accepted for a special issue of American Mineralogist focused on carbon in Earth and planetary materials. Co-I De Gregorio is serving as a guest editor for that issue. In December 2019 he traveled for the second year in a row to the Princess Elizabeth Antarctic Station (operated by Belgium). He is leading a team of Turkish scientists on an expedition to search for meteorites on the blue ice sheets near the research station.

Dr. Neil Bowles (University of Oxford) is a RISE2 collaborator, providing a link to the UK and broader European Solar System science and exploration communities.

3. Public Engagement Report

In 2020, RISE2 team members adapted traditional outreach activities for success in virtual environments and ramped up efforts to support digital, asynchronous public engagement.

3.1. Graduates for Education and Outreach (GEO)

Stony Brook University's RISE2-funded GEO program works to supply science education and communication to local New York schools. GEO met the challenge of providing hands-on science education during the pandemic by expanding its reach through online platforms in 2020. The GEO team, led by SBU graduate students Laura Breitenfeld and Ella Holme, recently began a partnership with Suffolk County Community College, delivering technical skill workshops for students in the geosciences as well as panel discussions focused on career paths and skills needed to become a scientist. GEO also maintained an outreach program with four fifth-grade classrooms at Nathaniel Woodhull Elementary School in Shirley, New York. At Woodhull, the team augmented lessons on topics such as water pollution and ecosystems with hands-on activities that helped students learn through experimentation, observational science, and art. In preparation for the arrival of the Perseverance Rover at Mars, GEO continued to share information about Mars geology and this exciting mission with students of various ages at additional schools and science fairs.

3.2. International Observe the Moon Night

RISE2 team members provided multi-pronged support for International Observe the Moon Night, an annual, worldwide public engagement event which was estimated to have reached an unprecedented 500,000 participants in 2020. SA/CS/PE lead Caela Barry joined the International Observe the Moon Night coordinating committee in April 2020, contributing to significant program modifications that enabled widespread virtual and small-group participation. Theme 2 Co-lead Kelsey Young gave twelve news interviews that were broadcast to audiences across the U.S. and around the world as part of a NASA Live Shot campaign. Patrick Whelley hosted a satellite event based in Middlebury, VT.

3.3. Planetary Analogs Website Collaboration

Co-I Patrick Whelley contributed field work photos for use on NASA's new Planetary Analogs web page. This project is led by SSERVI's GEODES team and will be hosted on https://solarsystem.nasa.gov. Its Phase 1 launch, slated for early 2021, will provide a brief, approachable introduction to planetary analogs, with an emphasis on geologic analogs. SA/CS/PE lead Caela Barry supported the Phase 1 launch by writing and editing content, integrating contributions from scientists, and packaging assets for use by web developers.

3.4. Additional Virtual Outreach Activities

P.I. Tim Glotch continued to provide public updates via the RISE2 Twitter account throughout 2020. Two high school students helped Bruce Demple's team to develop image analysis of the effects of lunar regolith simulants on lung cells in culture. Reporters highlighted Collaborator Ed Cloutis' contributions to OSIRIS-REx (https://bit.ly/3ok4IhG) and plans to prototype a Raman spectrometer for lunar surface exploration (https://bit.ly/38ceWoW). SA/CS/PE lead Caela Barry shared information about the RISE2 team's work as part of a presentation to the National Science Teaching Foundation's Aerospace Advisory Board.

Figure 6. Image submitted for use in Planetary Analogs website galleries. Credit: NASA/UMD/Patrick Whelley.

4. Student/Early Career Participation

Undergraduate Students

1. Jack Bauer, Stony Brook University, Software development to process images of dust-treated mammalian cells.
2. Conor Burbige, Stony Brook University, Machine learning applied to ordinary chondrite classification.
3. Leonard Flores, Stony Brook University, Synthesis of space weathered lunar regolith simulants.
4. Kellie Gunning, Stony Brook University, Furnace design for lunar degassing experiments.
5. Emery Ann Hansen, University of Texas El Paso, Kilbourne Hole UAS data analysis (graduated).
6. Alexandra Hilding, University of Texas El Paso, Kilbourne Hole UAS data analysis.
7. James Kim, Stony Brook University, Improving methods to assess mitochondrial function in dust-treated human lung cells.
8. Alexander Kling, Stony Brook University, Raman spectroscopy of impact-shocked basalts (graduated).
9. Stephanie Marquez, University of Texas El Paso, Kilbourne Hole UAS data analysis (graduated).
10. Barbara Morrow, Stony Brook University, Development of the "comet" assay to measure damage to the genome of human lung cells by lunar regolith simulants (graduated).
11. Sydney Wallace, PSI, Machine learning methods applied to asteroid and meteorite spectral classification.
12. J. Charles Western, PSI, Software development for optical constants calculation.
13. Alexandr Wolf, Stony Brook University, Analysis of inflammatory processes after exposure of primary cells to lunar regolith simulants.

Graduate Students

14. Laura Breitenfeld, Stony Brook University, Outreach with local New York elementary schools, high schools, and community colleges.
15. Tristan Catalano, Stony Brook University, Synthesis of space weathered lunar regolith simulants.
16. Hsing-Ming (Jamie) Chang, Stony Brook University,

Assessing the genotoxic and cytotoxic effects of lunar dust simulants on human lung cells.

17. Marina Gemma, Columbia University, Simulated asteroid environment spectroscopy of ordinary chondrites

18. Donald Hendrix, Stony Brook University, Assessment of the reactivity of lunar regolith simulants.

19. Ella Holme, Stony Brook University, Outreach with local New York elementary schools, high schools, and community colleges.

20. Reed Hopkins, Stony Brook University, Visible/near-IR spectroscopy of experimentally space weathered minerals.

21. Gregory Smith, Stony Brook University, In vivo (intratracheal) exposure of mice to lunar regolith simulants.

22. Connor Tinker, Stony Brook University, Development of a dust deposition chamber for infrared analyses of dust-coated surfaces.

23. Jordan Young, Stony Brook University, Raman and nano-IR spectroscopy of chondrite meteorites.

Postdoctoral Fellows

24. Cherie Achilles, NPP Postdoc at Goddard Space Flight Center, Mineralogy of analog materials and in analog environments

25. Xinzhong Chen, Stony Brook University, Quantitative modeling of infrared and terahertz near-field signals.

26. Brittany Cymes, Naval Research Laboratory, Study of space weathering features of Apollo 17 regolith samples via scanning transmission electron microscopy (STEM)

27. Casey Honniball, NPP Postdoc at Goddard Space Flight Center, Spectroscopy of the Moon and in analog environments

28. Zachary Morse, Howard University at NASA Goddard Space Flight Center, Geochemistry and mineralogy in analog environments, augmented reality to enhance human exploration

29. Cheng Ye, Stony Brook University, Mineral optical constants and light scattering theory (graduated with Ph.D. from Stony Brook in 2020).

5. Mission Involvement

1. Lunar Reconnaissance Orbiter, Timothy Glotch, Diviner Lunar Radiometer Experiment, Co-I, Spectroscopy of the lunar surface.

2. Lunar Reconnaissance Orbiter, Neil Bowles, Diviner Lunar Radiometer Experiment, Co-I, Infrared instrument development and lunar surface spectroscopy.

3. OSIRIS-REx, Timothy Glotch, OTES, Participating Scientist Co-I, Asteroid surface and meteorite spectroscopy.

4. OSIRIS-REx, Deanne Rogers, OTES, Participating Scientist Collaborator, Asteroid surface and meteorite spectroscopy.

5. ORISIS-REx, Christopher Edwards, OTES, Participating Scientist Collaborator, Asteroid surface thermophysics.

6. OSIRIS-REx, Neil Bowles, Co-I/Sample scientist—spectroscopy, Meteorite sample spectroscopy.

7. OSIRIS-REx, Thomas Burbine, Collaborator/Asteroid scientist, Asteroid surface and meteorite spectroscopy.

8. ORISIS-REx, Ed Cloutis, Co-I/Asteroid scientist, Asteroid surface and meteorite spectroscopy.

9. Emirates Mars Mission, Christopher Edwards, EMIRS, Instrument Scientist, Infrared instrument development.

10. 2001 Mars Odyssey, Deanne Rogers, THEMIS, Co-I, Infrared spectroscopy and thermophysics.

11. 2001 Mars Odyssey, Christopher Edwards, THEMIS, Co-I, Infrared spectroscopy and thermophysics, Phobos thermophysical modeling.

12. Mars Science Laboratory, Christopher Edwards, Participating Scientist, Mars surface thermophysics.

13. Mars Science Laboratory, Darby Dyar, ChemCam, Participating Scientist, Development of machine learning algorithms for interpreting spectroscopic measurements.

14. Mars 2020, Joel Hurowitz, PIXL, Deputy P.I., X-ray instrument development.

15. Hayabusa2, Bradley De Gregorio, Initial Analysis Team, Analyses of insoluble organic matter

16. Hayabusa2, Kate Burgess, Initial Analysis Team, Analyses of fine-sale mineralogy

17. Hayabusa2, Rhonda Stroud, Initial Analysis Team, Analyses of insoluble organic matter and fine-scale mineralogy

18. Hayabusa2, Bradley De Gregorio, Kate Burgess and Rhonda Stroud have all been appointed to the Hayabusa2 Initial Sample Analysis Team. Their SSERVI-supported investigations of the functional chemistry of meteoritic organics, and space weathering of regolith materials from airless bodies has prepared them to apply scanning transmission x-ray and electron microscopies to the newly-returned Ryugu samples. Their results will contribute to the understanding of Ryugu regolith grain retention of solar wind volatiles, and the formation and processing histories of Ryugu organic matter.

19. OSIRIS-REx, Tim Glotch was an OSIRIS-REx Participating Scientist Co-Investigator during the asteroid encounter phase of the mission and is actively analyzing data collected by the OSIRIS-REx Thermal Emission Spectrometer (OTES). Advances made during Glotch's SSERVI-funded work related to state-of-the-art light scattering models and thermal infrared spectroscopy are being directly applied to OTES data analysis.

Toolbox for Research and Exploration (TREX)

Amanda Hendrix
Planetary Science Institute, Tucson, AZ

CAN-2 TEAM

1. TREX Team Report

The TREX team had a successful 2020, addressing science and exploration questions in our 4 themes including the creation of a UV-IR planetary spectral library, lunar and small bodies science and exploration, and, to bring all of these concepts together, field work including autonomous sample selection and hypothesis testing. Due to the pandemic, our planned in-person team meeting during the March LPSC meeting was scuttled, as was our field work (originally planned for April-May 2020, now planned for October-November 2021). Some of our laboratory work was slowed due to COVID-19 but we were largely successful in making good headway in that area. The TREX team was pleased to host a Zoom-based site visit in November, sharing progress with the other SSERVI teams and opening up further ideas for collaborations.

1.1. The TREX Fine-Particle Spectral Library

A primary goal of TREX work is the creation of a spectral library, covering ultraviolet (UV) through mid-infrared (MIR) spectra of fine-particle (<10 µm) terrestrial minerals, meteorite and lunar samples, measured under planetary conditions (under vacuum and at appropriate temperatures). A big effort this year was the production of "Frankenspectra" (Fig. 1) of UV to MIR data using the best pieces of each terrestrial mineral spectrum from three of the TREX labs (DLR, PSI, UW). These merged spectra will be uploaded to our Tetracorder software for use in identifying materials during TREX field work, and will also be submitted to the PDS GEO node for archiving (along with individual spectra from each lab) for use by the larger community. As an additional component of this study, we tested the compositions of all the minerals using XRD. Co-I Noe Dobrea conducted XRD measurements on the TREX mineral samples, from his "home lab." Early in the year, before travel restrictions were in place, several TREX team members attended the Lunar Dust Workshop (Feb 11-13), in Houston; Co-I Lane presented TREX lab measurements of fine-grained minerals to aid in lunar dust characterization.

The next component of the TREX spectral library is the meteorite measurements. Prior to covid, our meteorite samples were being prepped by the Meteorite Working Group at NASA JSC. Receipt of the meteorite samples was delayed due to COVID-19 lab closures, but we did receive the samples in October 2020 and are grateful for the efforts of the team at JSC. Meteorite samples have been prepared as slabs and powders and are currently

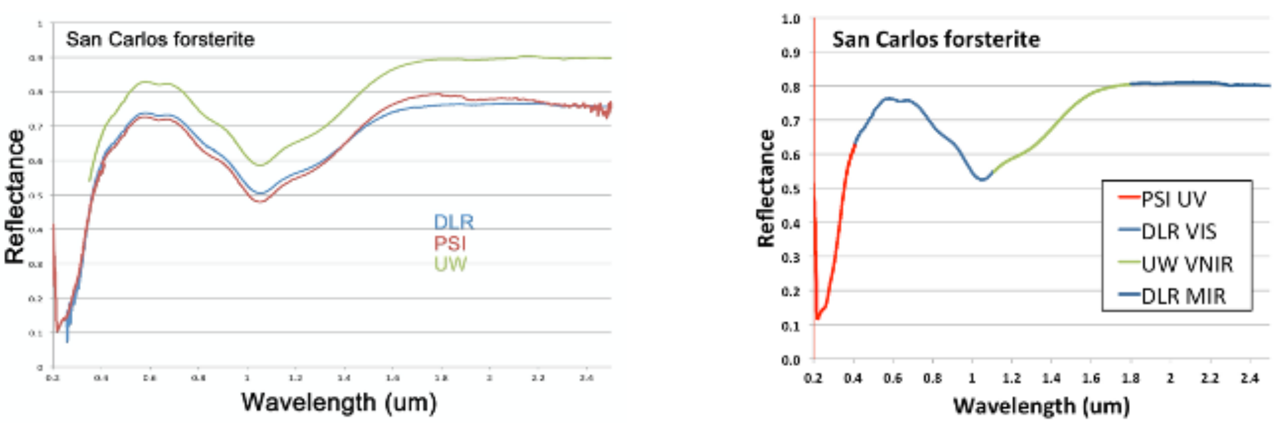


Figure 1. (left) Sample laboratory-measured reflectance data of a terrestrial mineral from the DLR, PSI and Univ. Winnipeg laboratories. The individual spectra are largely consistent but tend to have offsets, possibly due to sample packing differences. Spectra were merged into a single "Frankenspectrum" (right). These spectra show UV-near-IR data only; mid-IR data will also be merged, archived and used in field work.

being sent out to TREX labs for spectral measurements. We await word on our lunar sample requests.

1.1.1. Production of UV Standards

The TREX team decided (in 2019) that an additional important step for measuring samples in the UV is to produce a reflectance standard for use in the laboratory that is more reliable than the often-used Spectralon. Work on UV platinum standards is progressing, with Co-I Holsclaw leading the effort. Progress was slowed due to lab closures related to COVID-19. However, as a set of test cases, Holsclaw ordered 3 sets of different grits of glass diffusers and had them coated in platinum in a laboratory at the University of Colorado. Early in 2021, the team will be assessing which grit will be most acceptable for UV lab measurements. We will have roughly a dozen standards produced, for use in TREX labs and to distribute to our colleagues. We look forward to UV lab measurements using the new platinum standards in 2021. Such measurements will be the new state-of-the-art in UV reflectance measurements.

1.2. Lunar and Small Bodies Studies

Numerous investigations to characterize the Moon and small bodies, in preparation for future exploration, are being undertaken by the TREX team. Here we highlight a few of the studies and progress from 2020.

Co-I Lynnae Quick is working with Co-I Noah Petro and colleague Patrick Whelley on modeling lunar pyroclastic volcanism in Orientale basin. Part of this modeling involves constraining the amount of volatiles that were released during the eruption. Lynnae is also working with Dan Moriarty, Jacob Richardson and Steve Scheidt to determine the origin of Mafic Mound in South Pole Aitken Basin (SPA). Mafic Mound is an unusual volcanic feature located at the center of the ~2500 km SPA. Integrating its composition, morphology, and gravitational signature, Dr. Quick is working to construct a formation model of Mafic Mound, drawing on principles of volcanology and comparisons to a terrestrial analog. Understanding the formation of this unique lunar volcano will further reveal the diverse manifestations of impact basin-related magmatism within our solar system, and provide essential context for upcoming missions.

Co-I's Rebecca Ghent and Norbert Schorghofer are revising the Diviner thermal model to calculate grain sizes across the Moon, in a more flexible and faster way. They are working to complete a lunar grain size map that will be used by other investigators on the TREX team in various lunar analyses, for instance in understanding how grain size could be related to hydration.

TREX student Camilo Jaramillo Correa has been making great progress setting up the laboratory at UIUC for solar wind space weathering experiments, including designing a vacuum suitcase for transfer of samples from preparation (grinding) in the glove box to the vacuum chamber for reflectance measurements and irradiation. Irradiation and spectral measurements will be completed in 2021.

Co-Is Amy Mlinar and Edgard Rivera-Valentin are working on simulating impact-induced mixing on the Moon and predicting locations of exposures of olivine-rich materials in ejecta blankets of impact craters (Fig 2, top). They have created a fully 3-dimensional model of impact-induced excavation (Fig. 2, bottom) and have made recent changes to the model code that provide insight into what happens when we subject a two-layered Moon, 40 km thick crust (anorthosite) and mantle (75% olivine by volume), to the late heavy bombardment. Impacts excavate deep material onto a layered planet and can excavate mantle onto the surface. The resultant locations and amounts of olivine-rich material reveal insights about initial crustal thickness.

TREX Co-I Maria Banks has been working with GEODES P.I. Nick Schmerr on a project to construct a probabilistic seismic hazard analysis (PSHA) framework for the

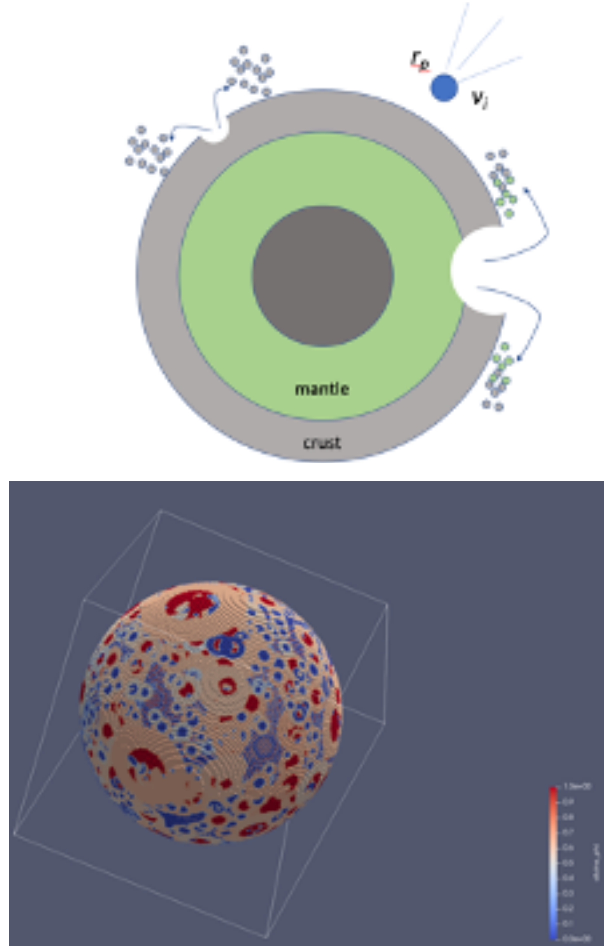


Figure 2. (top) schematic representing how deep impacts can probe mantle materials; (bottom) fully 3-D model for a 20 km crust case.

The vertical structure of the lunar crust can be sampled through studying outcrops of material excavated from the crust and mantle of the Moon located in/near large impact crater features.

Moon. This work is based on lobate scarp thrust faults, which are widespread across the lunar surface; some are likely currently active. Their locations, combined with newly developed lunar seismic ground motion scenario shake-maps and data from the Apollo-era seismic network on distributed seismicity and the nature of the subsurface, collectively offer the components needed to develop a preliminary PSHA for the Moon.

The PSHA calculations involve (Fig. 3):
1) integrated information regarding the location and magnitude of possible seismic sources and their estimated frequencies of occurrence (seismic source model)
2) estimates of ground motion attenuation (ground motion model)
3) the effect of the near-surface on the amplification of ground motions (site response model)
The Goal: Estimate the probability and severity of ground motion globally and at high priority landing sites. These analyses will provide a resource for evaluating seismic hazards both globally and at high priority landing sites (e.g. Fig. 4) - especially at locations of extended surface operations or permanent structures.

Lobate scarp thrust faults are widespread across the lunar surface; some may be currently active and present the need for a seismic hazard analysis to prepare for human missions to the Moon.

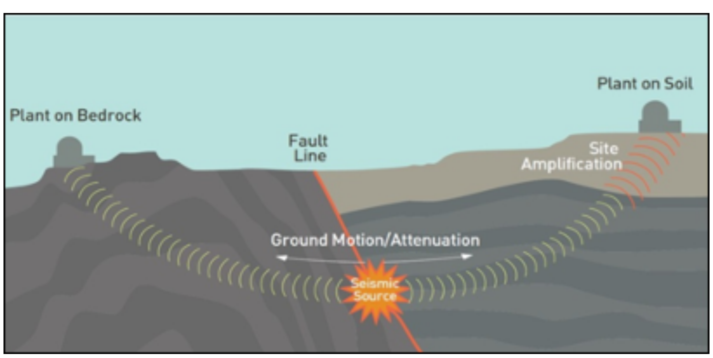


Figure 3. Schematic diagram of PSHA components (see 1, 2, and 3).

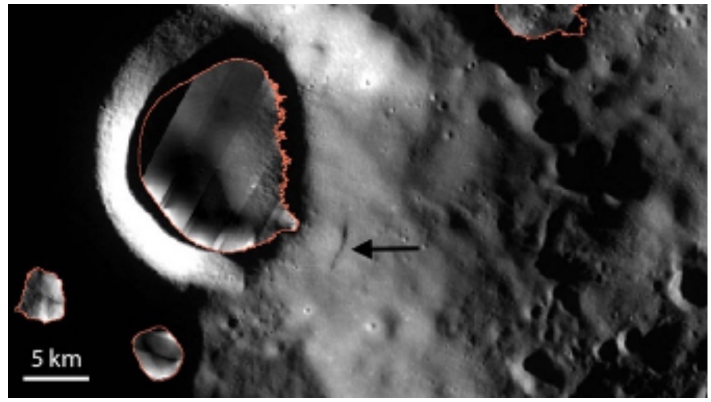


Figure 4. LROC WAC mosaic showing a lobate scarp (Shoemaker, black arrow, 86.28°S, 54.68°E) and nearby Permanently Shadowed Regions (outlined in orange).

11 years of LRO Diviner temperature data, incorporating diurnal and seasonal cycles, have been processed to characterize micro cold traps on the Moon and their role in storing volatiles.

TREX Co-I Norbert Schorghofer was involved in two papers in 2020 that studied the effects and importance of lunar micro cold traps for storing volatiles. Schorghofer & Williams (2020) performed an analysis of time-dependent Diviner temperatures, providing new maps of cold traps, subsurface ice stability, and vapor pumping. They showed that cold trapping is not the only ice storage mechanism; in vapor pumping, adsorbed water molecules can migrate into the subsurface; under some conditions this leads to net deposition of ice in the subsurface. A separate analysis of scale-dependence of shadows and temperatures by Hayne, Aharonson and Schorghofer (2020) quantified the prevalence of micro cold traps and showed that most of these cold traps are <1m diameter, making them more accessible than large cold traps.

1.3. TREX Fieldwork Preparations

The TREX team had planned to go into the field April 27 to May 10, 2020, in the Hopi Volcanic Buttes (HVB). A Pre-Operations Readiness Test (PORT) took place on March 23. This test was used to go over the operations manual in order to familiarize all team members on the field plans and train the science team on a hypothetical operational setting. Field work has been delayed to the October-November 2021 time frame due to COVID-19 restrictions.

In preparation for field work, the Carnegie Mellon student team (under the direction of TREX Co-I David Wettergreen) has installed a second processor on the rover to handle the data processing that the rover will have to perform in the field; work was also done on the stereo cameras and on geometric calibration. Co-I Roger Clark finished preparing Tetracorder software for the rover and has been working with the CMU team on installing and testing it on the rover. Co-I Eldar Noe Dobrea is working with CMU to define the rover operations with respect to the hypothesis map. In terms of instruments for field work, Co-I Tom Prettyman performed successful field testing of the Gamma Ray Spectrometer (GRS) on January 5 (Fig. 5) and is working on preparing it for future rover integration; he has also written a script to get the acquisition software and peak-finding software to work together on a pc stick.

Figure 5. Tom Prettyman tested his field portable GRS instrument on Jan 5 in Cundiyo area of N. New Mexico (shown: Dave Vaniman).

1.4. SSERVI EDI

NASA SSERVI has stepped up to take a leading role in equity, diversity, inclusion, and ethics issues within lunar/asteroid science, and in human exploration. SSERVI has formed the EDI Focus Group, to be led by TREX Team Member JA Grier. Interested parties in SSERVI-related science, education, communication, and industry have been invited. More than 60 people joined the email list, including several additional TREX investigators.

2. Inter-team/International Collaborations

In February, TREX P.I. Amanda Hendrix visited Orlando to meet with CLASS team members, give a seminar and discuss collaborations (see photo below).

TREX team members Faith Vilas, Amanda Hendrix and Deborah Domingue are working with JAXA partners on the Hayabusa-2 mission to study samples from Ryugu in TREX labs on Earth.

TREX Co-I Maria Banks is working with the GEODES team on a probabilistic seismic hazard analysis framework for the Moon (see Sec 1.2).

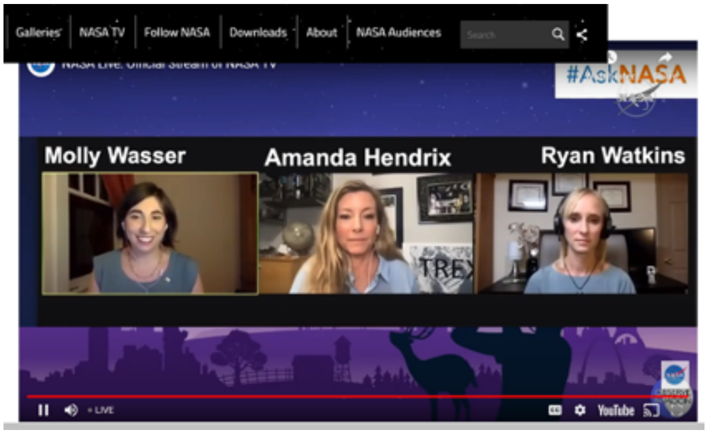
TREX Co-I JA Grier collaborated with the RISE2 team in presenting a virtual seminar on the Ethics of Space Exploration (see photo below).

3. Public Engagement

Under the guidance of Public Engagement Lead Sanlyn Buxner, the TREX team has excelled in virtual public engagement opportunities during this period of social distancing. Here we outline a number of the outreach activities undertaken by the TREX team in 2020.

3.1. International Observe the Moon Night

On September 26, TREX P.I. Amanda Hendrix and Co-I Ryan Watkins supported International Observe the Moon Night by participating in the NASA livestream event.



3.2 Planning for Workshop for Disabled Writers

TREX Co-I JA Grier is working with several individuals and fellow TREX colleagues on education/outreach initiatives, including a 7-week workshop for disabled science writers to be offered online in the fall of 2021.

Disabled people are a critically underserved population in all areas of STEM. Understanding that only disabled providers know how to best reach their disabled audiences, we will engage a group of disabled writers to: (1) enhance their science content, and (2) enhance our own capabilities to reach this notably underserved group. We anticipate that the workshop will produce new voices in STEM that include disability and intersectional concerns, increased understanding of (a positive view of) science and the scientific process, more vectors to encounter informed STEM people (social media, advocacy groups, writer's platforms, creative writing, etc.), and an increase in science literacy and critical thinking.

The planned workshop structure:

- Each week has two virtual 90 min sessions
- Week 1 – Introductions, Initial Evaluation, Troubleshooting
- Weeks 2-6 – Each session includes one TREX scientist presentation along with background and synthesis provided by facilitators
- Week 7 - Wrap up and final projects. Final evaluation

3.3 Meteorite Kits

As part of the TREX outreach effort, we have produced nine meteorite kits to be used by team members as outreach events. These will be used in Tucson, New Mexico, St. Louis, Washington/DC/Baltimore (2), Northern California, Southern California, Pittsburg, and Colorado, corresponding to the places that active TREX public engagement team members live and work. These kits will also be available to other SSERVI and SMD outreach teams for use in outreach events. Each set of samples is protected in a Pelican Box and comes with posters and handouts for interpretation. PSI has worked with numerous museums to create support materials for interpretation and has trained hundreds of volunteers with varying science expertise to engage the public with such kits (see figure below). In addition, comet making kits will be at each site with mostly consumable materials.

One of the TREX meteorite kits distributed to TREX team members around the county for use in outreach activities.

3.4 Chabot Space and Science Center Summer Lecture Series and Ongoing Volunteer Training

The TREX team has been working with Chabot Science in Oakland, CA on a summer lecture series and volunteer training. The following is a listing of the date, name and topic of each TREX presentation. We plan to continue this activity in 2021.

June 20 Thomas Prettyman - Dawn of Psyche

June 27 Deborah Domingue - Asteroids

July 11 George Kramer - Weirdness of the Moon: Lunar Swirls

July 18 A Grier - Impact Craters and Their Stories

August 1 Melissa Lane - Hunting for Meteorites in Antarctica

August 15 Maria Banks-Solar System Detective Work!

3.5 Howard University Bi-monthly Meet-with-a-planetary Scientist

The TREX team worked with Professor Marcus Alfred in the Department of Physics and Astronomy at Howard University to organize a bi-weekly lunchtime meet-and-greet with physics students. Howard does not currently have a Planetary Science program, but members of the TREX team have met with interested students, in a casual virtual environment, to talk about what we do and the different career paths that we each have taken. We will be continuing this program in 2021.

Oct 2 Deborah Domingue

Oct 16 Amanda Hendrix

Oct 30 Faith Vilas

Nov 13 Tom Prettyman

Dec 4 Daniel Wolf Savin

4. Student/Early Career Participation

Undergraduate Students

1. Brent Lorin, Johns Hopkins University, Whiting School of Engineering
2. Christian Cooper, Brown University, Department of Earth, Environmental, and Planetary Sciences
3. Rebecca A. Carmack, Purdue Univ., Planetary Science

Graduate Students

4. Alberto Candela, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.
5. Srinivas Vijayarangan, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.
6. Kevin Edelson, Ph.D. Candidate, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.
7. Camilo Jaramillo, Pennsylvania State Univ.
8. Eric Lang, Nuclear, Plasma, and Radiological Engineering Department, Univ. Illinois at Urbana-Champaign

Post-doctoral Researchers

9. Caroline Ytsma, Mount Holyoke College

5. Mission Involvement

1. Lunar Reconnaissance Mission (LRO), Noah Petro, Deputy Project Scientist, LROC, Diviner, LOLA; Amanda Hendrix LAMP Co-I; Maria Banks, LROC, Project Office: Science Data Manager, CLPS liaison and lead for landed mission support; Rebecca Ghent, Diviner; Ryan Clegg-Watkins, LROC; Faith Vilas, LAMP Co-I.
2. MoonRanger (CLPS LSITP payload): David Wettergreen - rover development as Co-I.
3. ExoMars Trace Gas Orbiter, Ed Cloutis, Co-I on NOMAD and ISM instruments.
4. OSIRIS-REx, Ed Cloutis; Rebecca Ghent; Jian-Yang Li; Amanda Hendrix (affiliate)
5. Mars Reconnaissance Orbiter (MRO): Maria Banks - High Resolution Imagining Science Experiment (HiRISE), Science team member, collaborator; Roger Clark - CRISM Co-I.
6. Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) Mission: Maria Banks - Science team member, collaborator.
7. Hayabusa 2, Faith Vilas, Deborah Domingue, Jorn Helbert.
8. Blue Origin - Ryan Watkins serves on Science Advisory Board and provides feedback regarding landing site selection and hazard analysis, as well as lunar-science related goals.
9. NASA International Space Station, EMIT, Roger Clark: Co-I.
10. NASA SBIR, Lunar Exploration Gas Spectrometer (LEGS), Roger Clark: Co-I.
11. Psyche - Tom Prettyman, Co-I, Light Elements Lead/ Gamma-Ray and Neutron Spectrometer Team.
12. LunaH-Map - Tom Prettyman, Co-I
13. Lunar Mineralogy and Surface Hydration Package (MaSH) - PRISM mission proposal that follows on from TREX work (Hendrix, Vilas, Clark, Banks; with DREAM-2 and FINESSE team member Tony Colaprete and LEADER Co-I O.J. Tucker)
14. LunaR: A Versatile Raman Spectrometer for Lunar Exploration (P.I.); FROST: Frozen Regolith Observation & Science Tools (Co-I): Ed Cloutis has a couple of recently-funded proposals that take advantage of TREX work on spectral properties of analogues and lunar samples. Both are funded by the Canadian Space Agency. Cloutis is P.I. on one of them and Co-I on another.
15. Daniel Wolf Savin is constructing an apparatus at Columbia Univ. to ion irradiate regolith-like loose powders, as a follow-on to TREX work. This is funded by a Solar System Workings grant. Part of the project involved a system to study the visible to near infrared (VNIR) spectral changes of the irradiated powders.
16. Maria Banks is a collaborator on a DDAP (Mercury) and LDAP proposal; the work is connected to TREX

work with lobate scarps and these features as targets of scientific interest and potential hazards and sites of resources for future exploration. Maria also serves on several Artemis working groups, including the Lunar Landing site planning and design group and the Artemis Science Objective Definition Technical Assessment Team. Some of this involvement stems from our TREX work, as well as interest in the abstract I submitted to the LSSW regarding our work and future surface ops on lobate scarps."

6. Awards

Ryan Watkins was awarded the 2020 SSERVI Susan Niebur award, given annually to a researcher who is within ten years of receiving their Phd, who has made significant contributions to the science and/or exploration communities.

Faith Vilas was named as a member of the American Astronomical Society's inaugural Fellows program. AAS Fellows are recognized for original research and publication, innovative contributions to astronomical techniques or instrumentation, significant contributions to education and public outreach, and noteworthy service to astronomy and to the Society itself.

Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)

Andy Rivkin
Johns Hopkins University/ Applied Physics Lab, Laurel, MD

CAN-1 TEAM

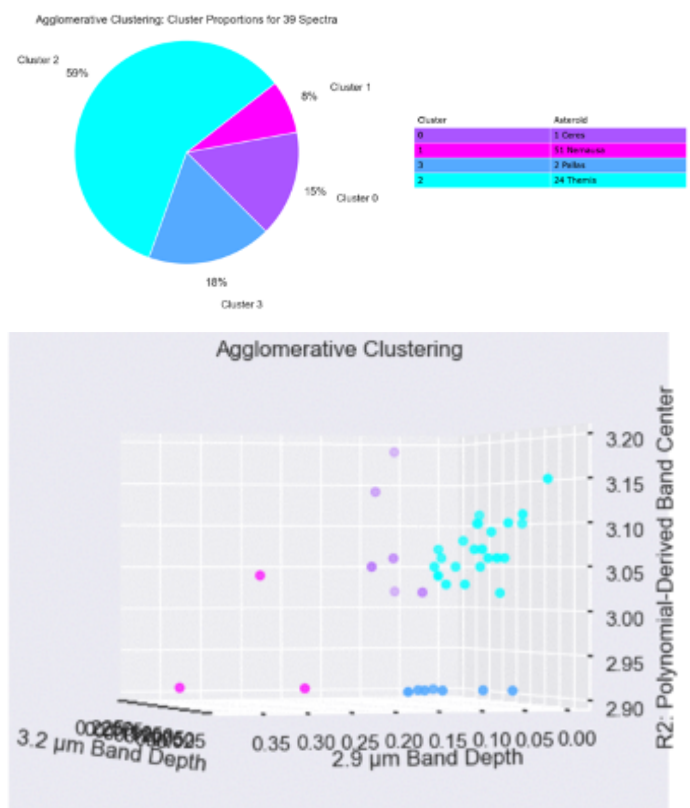
1. VORTICES Team Report

1.1. Writing and Wrapping Up

In early 2020, the VORTICES team began its final year in SSERVI with roughly 10% of its support remaining. The VORTICES period of performance ends shortly after this report submission. As a result, 2020 was devoted to a combination of tying up loose ends, supporting publications, and taking advantage of projects of opportunity. While the pandemic foiled some plans and complicated others, VORTICES had a productive year with our remaining funds. Prior to the pandemic, we had initial plans to focus 2020 on disseminating our work via conference attendance and manuscript writing, including a VORTICES writing retreat. COVID-19 put a kibosh on those plans, but we still were able to support several writing projects. In addition to the ones mentioned in the following sections, VORTICES support also was used by Dr. Debra Buzckowski to write a chapter on Vesta Geomorphology for the upcoming Cambridge University Press book "Vesta and Ceres: Insights into the Dawn of the Solar System" (in review), by Dr. Benjamin Greenhagen to partially support his work on an ISSI paper about volatile cold traps on the Moon, Mercury, and Ceres, and for his contributions to an ISSI paper about near-surface thermal properties of airless bodies, by Dr. Rachel Klima to write a chapter about the Moon for a new edition of the Encyclopedia of Geology, and by Dr. Matthew Richardson for "The CosmoQuest Moon Mappers Community Science Project: The Effect of Incidence Angle on the Lunar Surface Crater Distribution," to be submitted this week to a planetary science journal.

1.2. Asteroid Projects

Richardson and his postdoc mentor Dr. Andrew Rivkin (VORTICES P.I.) have been investigating machine-learning approaches for establishing a taxonomy for asteroids based on their reflectance spectra in the 2—4-µm region. The initial studies have used a set of spectra published by Rivkin et al. (2015, 2019) of the hydrated mineralogy of low-albedo C-complex asteroids, with the band center and band depths at 2.9 and 3.2 µm used as inputs. Initial results (Figure 1) suggest that four groups exist in the sample, similar to what was seen in previous informal taxonomies determined by inspection, with one previously-existing group seen by the machine learning algorithm as actually being two groups. Future work using other support will be used to extend this pilot work to account for observational uncertainties and increase the number of parameters being used to establish the groups. This work was presented at EPSC and AGU.



Cluster	Asteroid
0	1 Ceres
1	51 Nemausa
3	2 Pallas
2	24 Themis

Figure 1: Initial results from a machine-learning investigation of C-complex asteroid spectra in the 2—4 µm region suggest that they fall into four groups based on absorption band depths and positions (seen in the top pie chart and the bottom 3-D plot. This pilot study supported by VORTICES will be completed using additional funding from other sources.

Dr. K. T. Ramesh and his graduate student Ms. Sakshi Braroo focused their efforts on modeling material fractures towards including size effects and improving the physics incorporated to better predict strength outcomes at large scales. Such an effort hinges on the development of a refined micro-mechanics based analytical model for predicting the strength of rocks under high and very-high strain rates. Consequently, they worked towards developing such a framework that incorporates the stochasticity of the microstructural features in greater detail and thereby captures the coupling of size and rate effects in rocks. The result was the derivation of a simple analytical model for idealized microstructure and loading conditions. Support for this work transitioned to other funding at JHU at the end of summer 2020 given the completion of the subaward with VORTICES.

VORTICES-supported work using the asteroid thermal modeling code Sherman continued in 2020. Mary Hinkle, a student at the University of Central Florida, worked with Dr. Ellen Howell, Dr. Ron Vervack, and Rivkin to study the rotationally-resolved thermophysical properties of 433 Eros, finding that all but one of 29 spectra are consistent with either a thermal inertia of 50-200 or 150-400 (in SI units), with a crater fraction of 0.1-0.4. The average roughness and thermal inertia can only fit the mid-IR measurements if the geometric albedo is lower than that found by the NEAR Shoemaker mission. This work was presented at the 2020 DPS meeting. Vervack has been leading a similar study of the asteroid Phaethon, finding evidence of variation in thermal properties across its surface. This work is ongoing, but is planned for completion between this writing and the end of the period of performance.

VORTICES also supported Rivkin's preparation of and participation in several asteroid-related white papers submitted to the ongoing Planetary Science Decadal Survey. Of particular note is "Asteroid Resource Utilization: Ethical Concerns and Progress," which brought together subject matter experts and space ethics experts in the cause of making humanity's future in space one that enriches humanity's experience on Earth. Additional white papers that Rivkin contributed to while supported by VORTICES include "Strength in Diversity: Small Bodies as the Most Important Objects in Planetary Sciences" by Woodney et al., and "Main Belt Asteroid Science in the Decade 2023-2032: Fundamental Science Questions and Recommendations on Behalf of the Small Bodies Assessment Group" by McAdam et al. (2020). Both of these latter two white papers included Rivkin as the second author.

1.3 Lunar Research

One of the major VORTICES projects in our last months of support has been bringing the APL lunar lighting and communications evaluation tool "LunarShader" to a more user-friendly state. LunarShader-related work led by Dr. Ben Bussey was largely on hiatus during his time at NASA HQ, but with Bussey's return to APL there is a renewed desire for further development. LunarShader is designed to evaluate the lighting environment and availability of direct-to-Earth communication at a given site on the Moon over a user-defined time period. At the start of 2020, LunarShader only ran on a single desktop computer at APL, and required significant user input and knowledge, and post-processing in a different environment such as IDL. In the past 6 months, we have taken the original model that was limited in usability due to the requirement to run on windows-only systems, and converted it to run more efficiently on multiple systems, including high-performance clusters. The code was updated to run on GPUs v. CPUs more efficiently. We compared old simulations to the new modifications to ensure the code continued to provide accurate simulations. We updated post-processing tools to increase usability, including generating a pipeline to take processed lighting models into ArcGIS and the LRO Quickmap website. In late 2020 and early 2021, we have been collaborating with Dr. Matt Siegler and colleagues at NASA Ames to perform landing site analysis comparing our simulation and communications models with recent lunar data sets (including, for example, ice stability maps).

Analysis of lunar neutron flux data, a focus of the VORTICES team, continued in 2020. Drs. Josh Cahill, Jack Wilson, and David Lawrence have looked at several aspects of neutron measurements of the Moon. In addition to water, CO_2 ice has recently been reported in the coldest parts of lunar PSRs (Hayne et al., 2019). This CO_2 detection might inhibit access for ISRU to the water ice deposits that are known to be present in the PSRs. Wilson and Cahill worked to improve maps of neutron flux at the lunar poles to calculate the abundance and thickness of CO_2 frost in the PSRs and the depth to burial of H-bearing materials including water ice. These estimates will aid in the search for frost, ice and lag deposits in the PSRs. This trio is also working on a landing site case study at Schrodinger. The GRS and NS data are some of the most reliable data to use to determine what kind of compositional and hydration studies could be done in the area. In addition to the GRS/NS studies of Schrodinger, they also worked with Myriam Lemelin, who is creating new mineral maps of the region. There is contrasting information returning from VISNIR vs. neutron data for the region in terms of the peak rings and the pyroclastic areas, and for volatiles. Finally, Wilson led a study to determine if the measurements made from the Chang'e 2 MRM microwave radiometer instrument could be used to detect ice at the lunar poles. Wilson et al. used an image reconstruction technique to show that anomalies in the MRM data do not correlate with Lunar Prospector neutron measurements, suggesting the MRM anomalies are measuring temperature differences but not the presence/absence of ice.

In addition to the work on neutron measurements, Drs. David Blewett and Lauren Jozwiak used VORTICES support to work on a manuscript entitled "Near-UV and Near-IR Reflectance Studies of Lunar Swirls: Implications for Nanosize Iron Content and the Nature of Anomalous Space Weathering." Based on the spectral character of swirls and comparison with lab spectra of soils and analog material impregnated with iron particles, they infer that swirl materials contain abundances of nanosize metallic iron (nsFe) corresponding generally to immature (though not pristine) or submature soils. However, the size distribution of nsFe in swirls is anomalous compared with normal lunar surfaces, with a deficiency in the smaller size range (< ~15 nm). This deficit in the smaller-size nsFe can be attributed to the decrease in solar-wind flux reaching the surface in swirls caused by shielding from crustal magnetic fields. As a result, they conclude that solar-wind exposure is the primary agent for production of small nsFe in normal lunar space weathering. Micrometeoroid bombardment, which is unimpeded by the presence of magnetic fields, is mainly responsible for production of larger nsFe (Britt-Pieters particles) in space weathering.

Finally, VORTICES took advantage of the "science of opportunity" associated with a lunar impact that occurred during a lunar eclipse in January 2019 (Figure 2, top). Multispectral observations over a wide range of wavelengths intended for eclipse observations were analyzed to determine the lightcurve of the impact, and that lightcurve was used as a constraint for impact modeling. Simulated lightcurves for a 30-cm rocky projectile impacting the Moon at 45 degrees or shallower, coming from the direction of lunar north are the best matches for the true lightcurve (Figure 2, bottom). This was to be presented at the cancelled 2020 LPSC, a published paper is in preparation although the sensitive nature of the sensors involved are slowing that process.

1.4 Laboratory Work

Laboratory work in 2020 was understandably slowed by the onset of COVID and the need to establish protocols for safety. Dr. Karen Stockstill-Cahill was able to borrow a binocular microscope from an APL colleague's laboratory for use at home from March-June, and use it to isolate plagioclase grains in 250-500 μm powders of Stillwater basalts from other phases (olivine, orthopyroxene, an unknown opaque phase, and interstitial quartz) in the rock powders. Despite COVID delays, a new spectrometer and upgraded microscope were installed and set up in the laboratory in September, enabling quantitative internal water measurements for comparison with our UHV measurements of nominally anhydrous minerals.

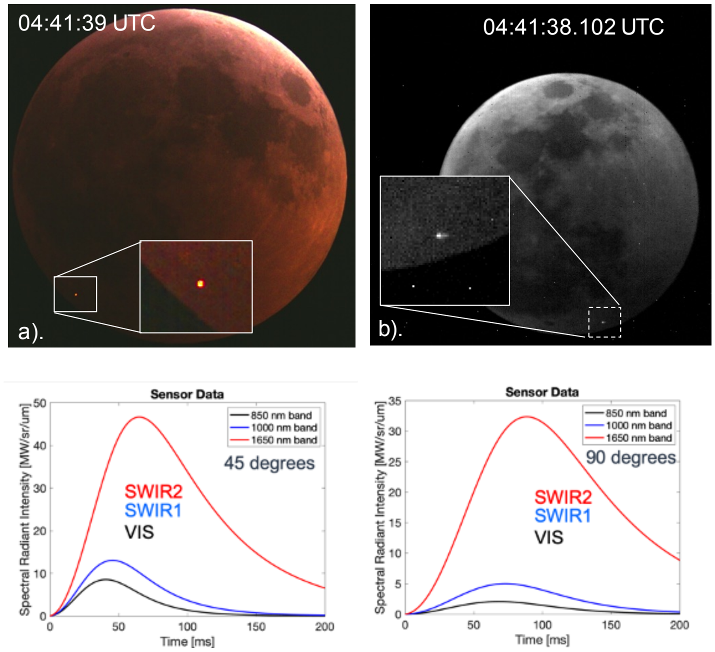


Figure 2: A flash during a January 2019 lunar eclipse has been modeled as due to the impact of a ~30-cm rocky body, at ~17 km/s. VORTICES funding supported data analysis and impact modeling, with a manuscript in preparation.

VORTICES has also partially supported the acquisition of laboratory spectra and the preparation of a manuscript investigating the relationship between the 3 and 6-μm hydration features in silicates, meteorite powders, and their analogs. Researchers are investigating the extent to which the 3-μm band varies with hydration by using the 6-μm feature to independently determine the presence of molecular water. One goal is to robustly determine from analysis of the 3-μm feature if the sample is devoid of molecular water (at several 10s of ppm). Another goal is to be able to determine if gross compositional identifications can be made through the inspection of the 3 and possibly the 6 μm absorption features. While not yet finished, we anticipate manuscript submission prior to the end of the period of performance. Honniball et al. (2020) used some of these measurements to estimate the water abundance in the lunar regolith in their paper on the detection of water in the lunar regolith using SOFIA.

1.5 Community Support

VORTICES support has also been used to allow members of the team to undertake important community service. Rivkin served on the Small Bodies Assessment Group Steering Committee, and Dr. Rachel Klima led the NESF SOC, helping determine how best to adapt NESF to a virtual meeting on short notice. VORTICES also supported other members of the SOC in their roles. Finally, VORTICES members participated in initial discussions setting up the EDI Focus Group and in ongoing discussions.

2. Inter-team/International Collaborations

With the winding down of the VORTICES team support, inter-team collaborations largely took the form of the continuation of long-term work and short, self-contained projects. Examples of the former include the ongoing collaborations between VORTICES and the RESOURCE, TREX and REVEALS teams, which have members in common, and the collaboration discussed above that led to VORTICES participation in the Honniball et al. SOFIA lunar observations paper.

3. Public and Student Engagement

In 2020, Public and Student Engagement activities built upon past SSERVI partnerships and leveraged resources to continue implementing a program that targets a diverse audience. Our activities engaged students, educators and the general public with SSERVI and VORTICES science and engineering themes. The COVID-19 pandemic introduced barriers in our ability to meet with our audiences in person, but we were able to do an in-person institute right before lockdowns went into place, and we participated in virtual activities for student engagement throughout the year.

The last in-person activity that we were able to do was the Solar System Exploration Public Engagement Institute (SSPEI). This 2-day event was held February 4-5, 2020, at the Lunar and Planetary Institute and at Space Center Houston. The event coordinated by Christine Shupla (Lunar and Planetary Institute) and Dr. M. Alexandra Matiella Novak (APL). Based on input from the leaders of NASA's Solar System Ambassador's program, the event was held in conjunction with the annual Space Exploration Educators Conference (SEEC) conducted by Space Center Houston. The Institute was attended by 17 scientists and educators (informal, formal, and Solar System Ambassadors) from across the United States, as well as 4 family members, and 4 presenters: Christine Shupla and Sha'Rell Webb (LPI), and Joelle Clark and Lori Rubino-Hare (Northern Arizona University). In April 2020, the EPO team followed up with the participants of the SSPEI to send them a list of resources that were requested during the Institute, as well as the updated Institute website listing all the activities from the Institute (https://www.lpi.usra.edu/education/solarsystem/activities). We presented on the outcomes of this Institute at the July 2020 NASA Exploration Science Forum with a poster titled "2020 Solar System Exploration Public Engagement Institute," with co-author Christine Shupla at LPI.

In October 2020, we supported the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) conference. We held a session called "Planetary Science and Exploration" and another on "Submitting a Competitive Internship Application." Both sessions had 80+ attendees each and were followed up with connections to new LatinX students who were looking for internship opportunities at APL and LPI.

4. Student/Early Career Participation

Given the winding down of VORTICES and the general uncertainty of 2020, we did not seek out student or early-career participation as we did early on in our period of performance. We can call out two people who fell into this category, however:

1. Sakshi Braroo: Graduate student at JHU working for Dr. K. T. Ramesh
2. Dr. Matthew Richardson: Postdoc at PSI working for Dr. Andy Rivkin

6. Mission Involvement

VORTICES helped support the following team members in analysis of data not otherwise supported by these projects, participation in projects for which other support is not available, and/or led to successful proposals for missions or mission participation:

1. LRO/Mini-RF, B. Bussey, P.I.
2. LRO/LAMP and Mini-RF, J. Cahill, Participating Scientist and Co-I

3. LRO/Diviner, B. Greenhagen, Deputy P.I.

4. LRO/Mini-RF and LAMP, A. Stickle, Science Team Member

5. NEA Scout, A. Rivkin, Co-I

6. Lunar Flashlight, B. Greenhagen, Co-I

7. DESTINY+, A. Rivkin, Collaborator

8. Lunar Trailblazer, R. Klima, Deputy P.I.

9. Korea Pathfinder Lunar Orbiter (KPLO), R. Klima, Participating Scientist

SSERVI (and previously NLSI) funding provided critical support for early studies of lunar water and minerals, which directly led to the science questions that will be addressed with the Lunar Trailblazer mission. Having a funded network of scientists both within and between SSERVI teams enables cutting edge science to be rapidly identified and pursued.

SUMMARY OF INTERNATIONAL COLLABORATIONS

SSERVI's International Partnerships Program provides collaboration opportunities for researchers within the global planetary science and human exploration community, working both on development of new science and technical approaches and communicating this science to the public. International partners are invited to participate in all aspects of the Institute's activities and programs. In addition, SSERVI's Solar System Treks Project (SSTP) has played a significant role in the institute's international partnerships and collaborative efforts are outlined in the sections below.

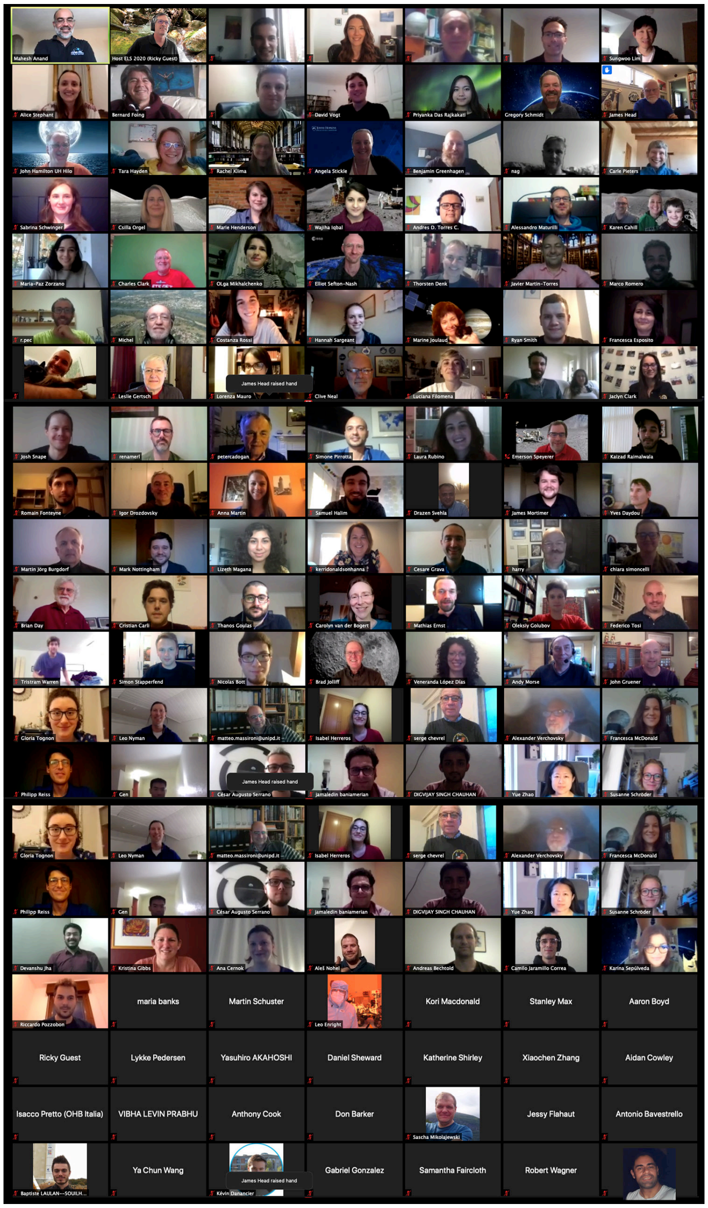
Non-U.S. science organizations can propose to become either Associate or Affiliate partners of SSERVI on a no-exchange-of-funds basis. Affiliate partnerships are with non-government institutions (e.g., universities and other research institutions). Associate partnerships are government-to-government agreements including those between NASA and international space agencies.
While SSERVI did not enter into an agreement with new partners in 2020, collaborations with the existing 11 international partners continued, although somewhat hampered by the worldwide COVID pandemic. SSERVI has active partnerships that include: Australia, Canada, France, Germany, Israel, Italy, Japan, Netherlands, Saudi Arabia, South Korea, and the United Kingdom. In addition, looking forwarded to 2021, SSERVI will be looking at strengthening existing partnerships and building new partnerships in conjunction with NASA's efforts to join with other nations through the Artemis Accords.
Below is a summary of the collaborations between SSERVI and the International Partners, followed by reports from some of the partners.

European Lunar Symposium

Due to the COVID-19 pandemic, the 8th European Lunar Symposium was held virtually with support from SSERVI. The meeting was held May e2020 This meeting built upon the European Lunar Symposiums (ELS) held in Berlin (2012), London (2014), Frascati (2015), Amsterdam (2016), Muenster (2017), Toulouse (2018) and Manchester (2019) as well as the global interest in new missions to the Moon. The meeting was held under the umbrella of the European SSERVI teams, supported by the local team at Manchester and SSERVI colleagues.

The format was similar to previous European Lunar Symposiums and consisted of both oral and poster presentations divided into four broad themes of: "Science of the Moon," "Science on the Moon," "Science from the Moon," and "Future Lunar Missions." There was a total of 87 virtual presentations made over two and a half days (66 orals + 21 posters). Approximately 470 individuals participated virtually representing the global community of lunar scientists and explorers and made this a highly successful event.

Photo Credit: ELS organizers



Australia

SSERVI leadership hosted Andrew Dempster and Serkan Saydam, leadership of the Australian Centre for Space Engineering Research (ACSER) at the University of New South Wales, at SSERVI Central on February 20, 2020. Discussions on space resources identified new opportunities for collaboration related to ISRU related activities with SSERVI and ACSER under the SSERVI-Australia partnership.

SSERVI continued working with our Australian partners at Curtin University in facilitating the expansion of the Desert Fireball Network (DFN) into the Global Fireball Observatory (GFO). These efforts focused on identifying new sites for GFO stations in Nevada and conducting initial discussions with the Association of Universities for Research in Astronomy (AURA) about potentially locating stations on Mauna Kea and Haleakala in Hawaii. SSERVI is also working with GFO in identifying strategies and potential partners in updating and expanding the scope of the Fireballs in the Sky citizen science application for the program.

Canada

In 2020, SSERVI's Director, Greg Schmidt, was asked to serve on External Executive Committee for the Institute for Earth and Space Exploration at Western University (https://cpsx.uwo.ca/). This Institute replaced the Canada Lunar Research Network, which was established as the first SSERVI international partnership in 2008.

Japan

SSTP's collaborations with JAXA this year focused primarily on support for their Hayabusa2 mission to Ryugu. The new Ryugu Trek portal was formally released at the 2020 JpGU conference. The portal facilitates visualization and dissemination of Hayabusa2 data. At JpGU, SSTP featured Ryugu Trek in a conference presentation and collaborated with JAXA is an online workshop they conducted in conjunction with the conference. In support of Hayabusa2's sample return to Earth in December 2020 and at the request of JAXA, SSTP produced custom visualizations and integrated them into a video their was used by JAXA for their public program for the sample return as well as for media event in Australia where the return was successfully conducted.

In support of the BepiColombo mission, SSTP continued its collaboration with JAXA through the Mercury Trek portal. An updated release included an expanded list of data products available, enhanced search capabilities, and internationalization of the interface with controls being made available in Japanese as well as English.

Italy

SSTP continued its collaboration with our Italian partners at the Italian National Institute for Nuclear Physics (INFN), testing and refining the Lunar LASER Retroreflector Geometry Tool prototype and advancing it from its prototype status to a released online tool now available in Moon Trek for account-level access.

France 2020 Report

Principal Investigator Patrick PINET
with contributions from N. André, I. Dandouras, J. Lasue, P.Y. Meslin

Overall Context

The French Institute for Research in Astrophysics and Planetology (IRAP, Toulouse) became a SSERVI partner after Principal Investigator Patrick Pinet submitted an excellent proposal for 'Space Studies of the Moon, Mercury, Asteroids and Comets in France' (SSMMAC-France). The official signing, in the presence of SSERVI Director Gregory Schmidt and representatives of the US consulate in Toulouse, was held on May, 24th, 2016.

Events, Meetings and Committees

Though not directly connected to SSERVI main objectives, IRAP is also heavily committed to Solar Orbiter and Mars-2020/ Perseverance missions, launched successfully on February, 10th, 2020 and July, 30th, 2020, respectively.

IRAP attended Microsymposium 60th and LPSC 50th meetings held in Houston (March, 20th-24th, 2019) and met with the SSERVI partners and staff at the EC meeting held on March, 19th. IRAP also regularly interacted with SSERVI officers and staff in order to prepare and organize the European Lunar Symposium (ELS) 7th and 8th meetings which occurred respectively, in Manchester (May 2019) and initially Padua (Italy), which turned into a virtual online meeting (May 2020) due to the pandemic.

N. André has been appointed member of an ad hoc Science Team by the Human spaceflight and Exploration Science Advisory Committee (HESAC) of ESA in order to prepare a strategy for science at the Moon. P. Pinet is, at the request of ESA, a member of the international Science Definition Team for the Human-Enhanced Robotic Architecture Capability for Lunar Exploration and Science (HERACLES) project. In preparation of the scientific payload of the Deep Space Gateway, I. Dandouras is chairing at ESA a topical team formed to support the definition of payload studies in the field of space plasma physics.

Outreach Activities

On the occasion of the 50th anniversary of the first man on the Moon (1969-2019), a book on the Apollo Expeditions has been published by S. Chevrel (Chevrel, S., Missions Apollo/Expéditions scientifiques sur la Lune, 471 p., ed. EMPREINTE, May 2019), with a number of related public conferences on the subject.

Science and Project Highlights

Lunar Orbital Imaging Spectroscopy and Geology:
Laboratory data are used to improve the capability of the Modified Gaussian Model (MGM) to realistically model complex mafic mineralogies and to accurately characterize olivine composition (Pinet et al, 2019, 2020), with implications for inferring the lunar crust subsurface mineralogy from orbital and/or in-situ visible near-infrared spectroscopy (Pinet, 2019).

The exploration strategy aims at linking spectral composition (M3: Moon Mineralogy Mapper imaging spectrometer) and morphological features at high resolution (LRO) (Chevrel et al., 2019) to better constrain the lunar crust lithology and cratering process. It has been tested on a few impact craters (e.g.,Copernicus and Eratosthenes) with the objective of documenting the local/regional petrology through the characterization of exposed outcrops (e.g., central peaks, inner wall, rims or on the floor) from plagioclase and mafic crystal field absorptions (Pinet et al., 2020).

Recently this has also been applied to Zhinyu crater (3.8km in diameter), one of the largest craters within a few tens of kilometers from the Chang'e-4 landing site located in Von Karman crater (186 km in diameter), lying in the northwest of South Pole-Aitken (SPA) basin on the lunar farside and flooded by mare basalts during the Imbrian period. Zhinyu crater is the product of a fresh impact that excavated subsurface, basaltic materials onto the surface. The compositional characteristics of the continuous ejecta around the crater vary radially with distance, suggesting possible mineral heterogeneity at depth. The derived mineral abundances vary radially and discontinuously from the crater rim outwards, forming compositionally distinct annuli. The variations in the mineral olivine and clinopyroxene abundances support the idea that there could be at least three distinct basalt layers within the Von Kármán crater (Gou et al., Icarus, in press).

Lunar Environmment / solar wind / interaction with the terrestrial magnetosphere

The Moon is a unique location to study the deep space plasma environment, due to the absence of a substantial intrinsic magnetic field and the direct exposure to the solar wind, galactic cosmic rays (GCRs) and solar energetic particles (SEPs). However, 5-6 days each orbit, the Moon crosses the tail of the terrestrial magnetosphere facilitating the in-situ study of the terrestrial magnetotail plasma environment as well as atmospheric escape from the ionosphere (Figure 1). When back outside of the magnetosphere, a variety of these and other phenomena, e.g. those driving solar-terrestrial relationships, can be investigated through remote sensing using a variety of imaging techniques. Most importantly, the lunar environment offers a unique opportunity to study the interaction of the solar wind and the magnetosphere with the lunar surface and the lunar surface-bounded exosphere (Dandouras et al., EGU, 2019; De Keyser et al., European Space Weather Week, 2019; Dandouras, ISSI, 2020).

The Lunar Orbiter Platform – Gateway (or Deep Space Gateway) is an international crewed platform that will be assembled and operated in the vicinity of the Moon in the early 2020s and will offer new opportunities for fundamental and applied scientific research (e.g. Dandouras et al., Space Sci. Rev., 2020).

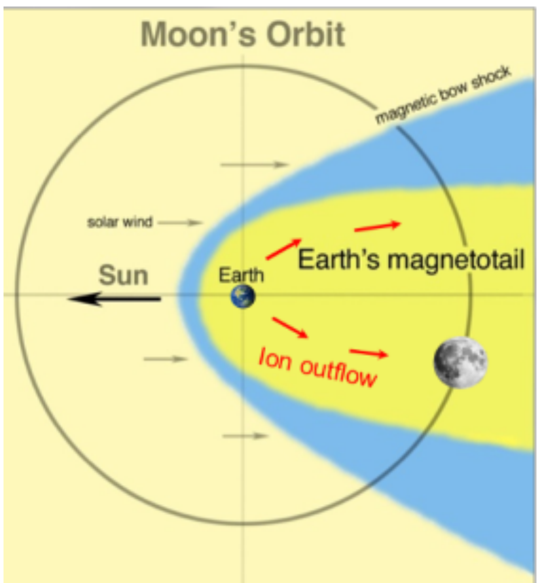


Figure 1. Moon's orbit with respect to the Earth's magnetosphere. Earth's and Moon's sizes not to scale.

In preparation of the scientific payload of the Lunar Orbiter Platform – Gateway, we formed a team that undertook for ESA a conceptual design study for a Space Plasma Physics Payload Package onboard Gateway (SP4GATEWAY). The main goal of this study (Dandouras et al., EGU, 2020) has been to provide first a science rationale for hosting space plasma physics instrumentation on Gateway, and then to proceed to a conceptual payload design addressing these objectives and is compatible with technical requirements (Figure 2). The Gateway modules that are best-suited for placing the in-situ measurement plasma instruments have been identified following a simulation we performed of the interaction between the Gateway and its plasma environment. The fields-of-view (FOVs) of the remote sensing instruments, as projected on the sky and on the celestial objects, were analyzed by simulating their evolution along Gateway's orbit.

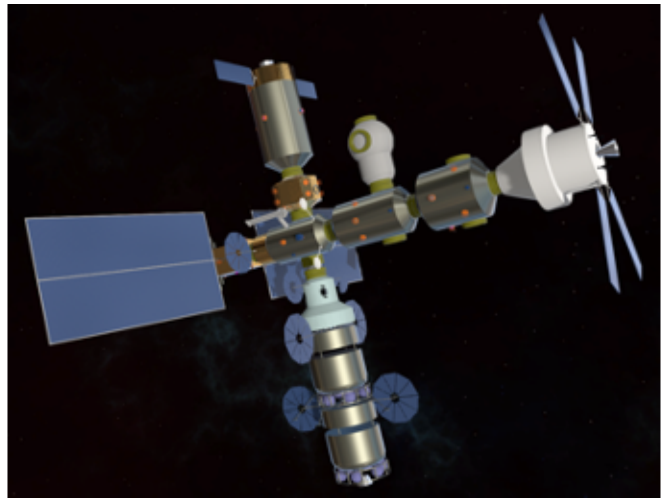


Figure 2. Example of a space plasma physics payload configuration onboard the Gateway studied.

Following this conceptual design study for a Space Plasma Physics Payload Package onboard Gateway, results indicate that Gateway is very well-suited for space plasma physics research with a series of scientific objectives that can be addressed.

Mercury

ESA/JAXA BepiColombo spacecraft is currently in cruise phase towards Mercury. IRAP has built the two Mercury Electron Analyzers (MEA) within the Mercury Plasma Particle Experiment onboard Mio, the japanese spacecraft of the mission. In 2020 new MEA observations were obtained (see Figure 3 below). BepiColombo has flown by the Earth in April and Venus in October. MEA was turned

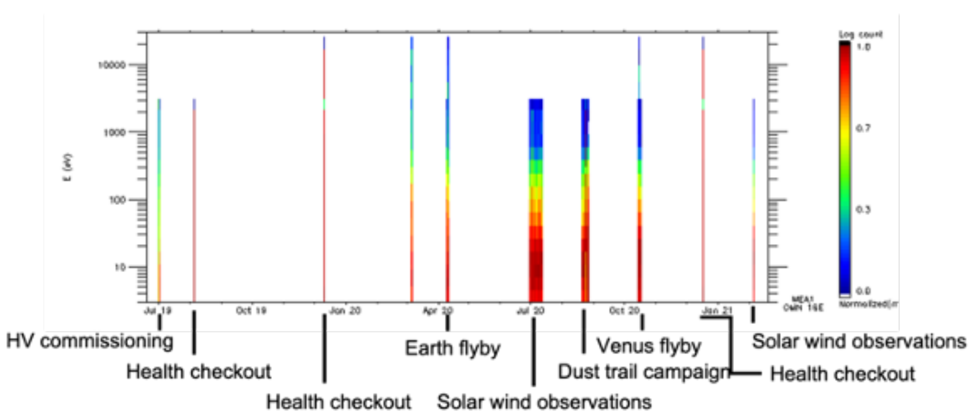


Figure 3. Bepi Colombo on its way to Mercury.

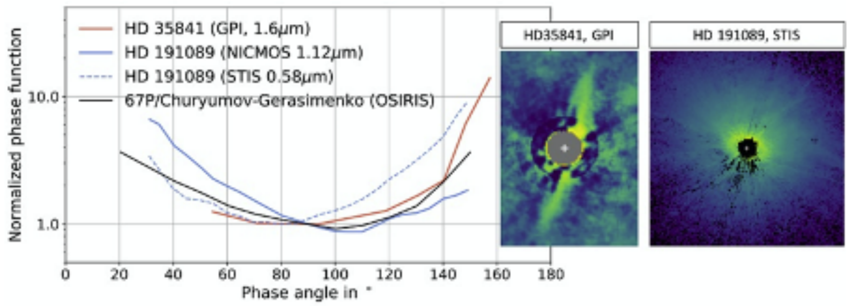


Figure 4. Comparison between brightness phase dependence for two debris disks and cometary dust. (Levasseur-Regourd et al. 2020).

ON during those flybys and obtained good scientific measurements currently under analysis. MEA was also turned ON in the solar wind during one planetary alignment in July 2020 and for a dust trail crossing in August 2020. The MEA Team in Toulouse is preparing for the second Venus flyby in August 2021 and the first Mercury flyby in October 2021. IRAP postdoc student Sae Aizawa analysed MESSENGER observations in the Hermean magnetosphere in order to study the non-adiabatic energization and transport of ions in Kelvin-Helmholtz vortices occuring in the flanks of the magnetosphere (Aizawa et al., PSS, 2020) and characterized the ion properties in the resulting structures (Aizawa et al., JGR, 2020). Sae Aizawa is also coordinating the Studies on Hermean magnetosphere Oriented Theories and Simulations (SHOTS) (http://shots-bepicolombo.irap.omp.eu) working group of the BepiColombo mission, which aims to share and compare numerical simulations results among the community (Aizawa et al., PSS, in press; Milillo et al., SSR, 2021; Mangano et al., SSR, 2021).

ROSETTA

Rosetta mission ended in late 2016 and IRAP has been involved in the data analysis and interpretation, with significant participation in the mission's dust working group dedicated to giving a multi-scale multi-instrument review of the properties of dust particles in the coma of 67P/Churyumov-Gerasimenko (Levasseur-Regourd et al, 2019; Güttler et al. 2019; Lasue et al. 2019, Hoang et al., 2020). Finally, J. Lasue participated in the review panel for the public release of the Rosetta end of mission data to the PSA and PDS.

IRAP teams continue their work on exploring the relationship between small bodies (asteroids, comets), the interplanetary dust and exozodiacal dust clouds. These studies are essential to better understand planetary systems formation, especially the optical and thermal properties of the dust particles during their accretionary stage. The focus is on comparing light scattering properties of dust particles (see Figure 4 below) studied in the Solar System, and observed in exoplanetary disks to better model their properties (Lasue et al. 2020; Levasseur-Regourd et al. 2020).

Future Lunar and Small Bodies Missions and Instruments

IRAP is currently involved in several missions proposals, with various ongoing collaborations with ESA, NASA, JAXA, CSA and the Chinese Academy of Sciences (CAS)/ Chinese Space Agency (CNSA).

Since 2012, Laser-Induced Breakdown Spectroscopy (LIBS) has been successfully used under low atmospheric pressure for exploring the geology of Mars at Gale Crater with the Mars Science Laboratory rover's ChemCam instrument. Laboratory studies performed at IRAP have also demonstrated that LIBS can give accurate and precise results under vacuum conditions. The potential of LIBS for rapid and accurate in-situ elemental analysis of lunar materials and characterization of potential resources for future lunar and planetary exploration is currently under study (Wiens et al., 2020). IRAP is collaborating on a NASA PRISM proposal Exploring Ubiquitous Regolith to Elucidate Kemical Analyses (EUREKA). This rover mission will seek to address outstanding science and in-situ resource utilization (ISRU) questions at Schrödinger Basin on the Moon using LIBS techniques.

IRAP is also participating to the NASA PRISM proposal Carruthers Integrated Payload Suite (CIPS) led by SwRI and intended to decipher the mysteries of Reiner Gamma Swirl, and to understand more of the relationships between magnetic fields, space weathering, maturity, hydration, and physical structure of the regolith in the lunar surface environment.

IRAP is also involved in the development of new space cameras based on the CMOS technology. These cameras equip the SuperCam instrument on-board the Perseverance Rover. These detectors are very versatile and could find their use in many configurations (e.g., Lasue et al., LPSC 2020).

Detection of Outgassing RadoN (DORN) Instrument

Since the early stages of the lunar exploration, radon-222 and its progeny (218Po, 214Po, 210Pb and 210Po) have been identified as key tracers of the present-day lunar seismic and venting activity. Long-term monitoring of the radon cycle on the surface of the Moon would thus provide valuable ground truth for orbital measurements and would help address several key issues related to the transport of lunar volatiles and dust, including the study of the transport of gases through the lunar regolith and of volatiles and dust in the lunar exosphere, the monitoring of the venting activity of the Moon and identification of active outgassing spots. An in-situ instrument for the Detection of Outgassing RadoN (DORN), has been selected to be part of the Chang'e-6 payload and is under construction at IRAP (e.g., Meslin et al., 2020). It is aimed at measuring both radon and polonium atoms around the lander, and the subsurface flux of radon at the Chang'e-6 landing site. The mission is scheduled to take place in 2023.

Figure 5. MMX mission of the Japan Space Agency JAXA (credit JAXA).

Small Bodies

IRAP-OMP is involved in the MMX project of the JAXA space agency by actively collaborating in the MMX Infrared Spectrometer (MIRS) French instrument. The MMX mission (Figure 5) will be launched in 2024 to explore the satellite system of Mars, Phobos and Deimos, and more specifically to collect Phobos samples and bring them back to Earth by 2030. MMX will therefore be able to decipher the still debated origin of the Moons of Mars. In particular, MIRS will explore the surface of Phobos, Deimos and Mars in the wavelength range 0.9 to 3.6 μm, which includes typical absorption bands for ice (3.0 – 3.2 μm), and document the geological context of the collected samples. IRAP is starting laboratory studies to explore how weathering by flash heating may affect the surface spectral behavior of Phobos.

ESA has selected its first fast-class mission in June 2019. Comet Interceptor will be the first space mission to explore a comet newly entered into the inner solar system ("dynamically new comet") or object from another solar system, with the first multi-point exploration of the comet's environment.

The Comet Interceptor mission will include three probes: a mother satellite and two daughter satellites, which will be launched towards the Lagrange L2 point with ARIEL in 2028 and remain parked in orbit at L2 until ground observations can identify the precise arrival of a comet that has newly entered the internal solar system with a trajectory that can be intercepted by the Comet Interceptor.

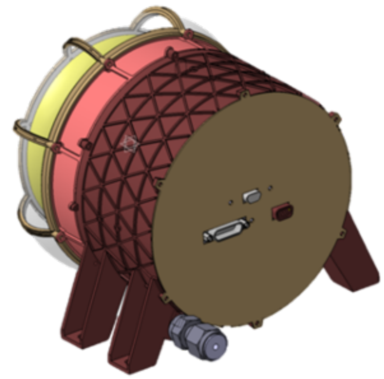


Figure 6. Sketch of the Low-Energy Electron Spectrometer (LEES).

The European contributions will be onboard the parent satellite and one of the daughter satellites, the second daughter satellite being Japanese. IRAP contribution is part of the Dust, Field and Plasma Consortium dedicated to in-situ multipoint measurements of ionized and dusty phases, as well as of the electromagnetic field in the cometary environment and its interaction with the Sun and the solar wind. IRAP will supply one miniaturized electron analyzer, the Low-Energy Electron Spectrometer (LEES, Figure 6) on the mother spacecraft to the consortium with the aim of identifying and measuring the main sources of cometary gas ionization. In 2020 Phase A/B1 of the project has started, and a full prototype of the instrument is being built, tested, and validated at IRAP, and should be delivered by the end of 2021.

References

Lunar Geology:

Pinet, P.C., Exploration lunaire : passé, présent et futur, journée Prospective Lune du CNES, Paris, 01/03/2019.

Pinet, P.C., S.D., Chevrel, Y.H., Daydou, Advanced spectroscopic software for olivine detection and composition Determination (ASS-OL), abs. #25, ELS 7th proceedings, May 2019.

S.D. Chevrel, P.C. Pinet, Y. Daydou, M. Loche, Large Impact Craters: Linking Spectral Composition (M3) and Morphological Features at High Resolution (LRO), abs. #27, ELS 7th proceedings, May 2019.

Pinet, P. C., Chevrel, S. D., Daydou, Y. H., 2019.

Reassessing the relationship between olivine composition and reflectance Spectroscopy from advanced MGM deconvolution. 50th Lunar and Planetary Science Conference, the Woodlands, Texas, pp. 1806.

Pinet, P.C., The Moon's mantle unveiled, Nature, Volume: 569 Issue: 7756 Pages: 338-339 (2019).

Karouji Y., Hiesinger H., Abe M., Haruyama J., Ohtake M.,Carey W., Picard M., Haltigin T., Hashizume K., Hasebe N., Ogawa Y., Yada T., Nagaoka H., Ishihara Y., Kayama M., Yamamoto S., Pinet P.C., Wöhler C., and Landgraf M., Heracles mission : Exploration and Sample Return of the Moon, ISTS 30th, 2019.

P.C. Pinet, S.C. Chevrel, Y.H. Daydou and D. Dhingra, Olivine Detection and Composition Determination at Copernicus and Eratosthenes Craters, ELS 8th proceedings, p. 102-103, held 12 -14 May(oral online), 2020. https://els2020.arc.nasa.gov/playback

Blanc, M., Pinet, P.C., Dandouras, I., Chevrel, S., P. Devoto, L'Exploration lunaire : une si vieille lune ?, Journées Scientifiques et Techniques de IRAP, 27-28 Février 2020.

Hiesinger, H., Wedler, A., Van Der Bogert, C., P.C. Pinet, Head, J.W., Anand, M., Ivanov, M., Jolliff, B., Lunar Volcanic Explorer (LVEX), proposal submitted to ESA call for Ideas "Ideas for exploring the Moon with a European Large Logistics Lander, July 2020.

S. Gou, Zongyu Yue, K. Di, R. Bugiolacchi, M.-H. Zhu, P.C. Pinet, Z. Cai, Mare basalt flooding events surrounding Chang'e-4 landing site as revealed by Zhinyu crater ejecta, Icarus, 2021, in press.

Lunar Environmment / solar wind / interaction with the terrestrial magnetosphere:

I. Dandouras, M. Blanc, L. Fossati, M. Gerasimov, E. W. Guenther, K. G. Kisllyakova, H. Lammer, Y. Lin, B. Marty, C. Mazelle, S. Rugheimer, M. Scherf, C. Sotin, L. Sproß, S. Tachibana, P. Wurz, & M. Yamauchi: Future Missions related to the determination of the elemental and isotopic composition of Earth, Moon and the terrestrial planets. Space Sci. Rev., Topical Collection: Reading Terrestrial Planet Evolution in Isotope and Element Measurements, Chapter 12, doi: 10.1007/s11214-020-00736-0, 2020.

I. Dandouras: Deep Space Gateway Moon Exploration. Invited communication at the ISSI Workshop "Surface bounded exospheres and interactions in the inner Solar System", Bern, January 2020.

I. Dandouras, R. A. Bamford, G. Branduardi-Raymont, D. Constantinescu, J. De Keyser, Y. Futaana, H. Lammer, F. Leblanc, A. Milillo, R. Nakamura, E. Roussos, J. Carpenter, & M. G. G. T. Taylor: Space Plasma Physics Science Opportunities for the Deep Space Gateway. Communication at EGU, Vienna, April 2019, and at European Lunar Symposium 7th, Manchester, May 2019.

J. De Keyser, I. Dandouras, R. A. Bamford, G. Branduardi-Raymont, D. Constantinescu, Y. Futaana, B. Grison, H. Lammer, F. Leblanc, A. Milillo, R. Nakamura, Z. Nemecek, L. Prech, E. Roussos, M. G. G. T. Taylor, & J. Carpenter: Space weather from lunar orbit: The Deep Space Gateway as a platform for space plasma instruments. Communication at the "16th European Space Weather Week", Liège, November 2019.

I. Dandouras, P. Devoto, J. De Keyser, Y. Futaana, R. Bamford, G. Branduardi-Raymont, D. Constantinescu, J.-Y. Chaufray, J. Eastwood, M. Echim, B. Grison, D. Hercik, A. Milillo, R. Nakamura, L. Přech, E. Roussos, Š. Štverák, A. Laurens, J. Winter, M. G. G. T. Taylor, J. Forest, A. Trouche, S. Hess, J.-C. Mateo-Vélez, D. Pheav, P. Garnier, B. Lavraud, E. De Angelis, J. Laifr, R. Lán, Z. Němeček, J. Šafránková, F. Leblanc, & X.-D. Wang: SP4GATEWAY: a Space Plasma Physics Payload Package conceptual design for the Deep Space Gateway Lunar Orbital Platform. Communication at EGU, Vienna, May 2020.

Mercury:

Aizawa, S., L. S. Griton, S. Fatemi, W. Exner, J. Deca, F. Pantellini, M. Yagi, D. Heyner, V. Génot, N. André, J. Amaya, G. Murakami, L. Beigbeder, M. Gangloff, M. Bouchemit, E. Budnik, H. Usui, Cross-comparison of global simulation models applied to Mercury's dayside magnetosphere, Planetary and Space Sciences. in press, doi: 10.1016/j.pss.2021.105176, 2021 .

Aizawa. S., J. M. Raines, D. Delcourt, N. Terada, and N. Andre, MESSENGER observations of planetary ion characteristics within Kelvin-Helmholtz vortices at Mercury, Journal of Geophysical Research: Space Physics, Volume 125, Issue 10, doi: 10.1029/2020JA027871

Aizawa. S., D. Delcourt, N. Terada, and N. Andre, Statistical study of non-adiabatic energization and transport in Kelvin-Helmhotlz vortices at Mercury, Volume 193, doi: 10.1016/j.pss.2020.105079

Milillo, A., M. Fujimoto, G. Murakami, J. Benkhoff, J. Zender, S. Aizawa, M. Dosa, L. Griton, D. Heyner, G. Ho, S. Imber, X. Jia, T. Karlsson, R.M. Killen, M. Laurenza, S. Lindsay, S. McKenna-Lawlor, A. Mura, J. Raines, D. Rothery, N. André,

W. Baumjohann, A. Berezhnoy, P.A.Bourdin, E. Bunce, F. Califano, J. Deca, S. de la Fuente, C. Dong, C. Grava, S. Fatemi, P. Henri, S. Ivanovski, B. V. Jackson, M. James, E. Kallio, Y. Kasaba, E. Kilpua, M. Kobayashi, B. Langlais, F. Leblanc, C. Lhotka, V. Mangano, A. Martindale, S. Massetti, A. Masters, M. Morooka, Y. Narita, J.S. Oliveira, D. Odstrcil, S. Orsini, C. Plainaki, F. Plaschke, F. Sahraoui, K. Seki, J. Slavin, R. Vainio, P. Wurz, S. Barabash, C. Carr, D. Delcourt, K.-H. Glassmeier, M. Grande, M. Hirahara, J. Huovelin, O. Korablev, H. Kojima, H. Lichtenegger, S. Livi, A. Matsuoka, R. Moissl, M. Moncuquet, K. Muinonen, E. Quemerais, Y. Saito, S. Yagitani, I. Yoshikawa, and J.-E. Wahlund, Investigating Mercury's environment with the two-spacecraft BepiColombo mission, Space Science Reviews, Volume 216, Issue 5, doi: 10.1007/s11214-020-00712-8, 2021

Mangano, V., M. Dosa, M. Fraenz, A. Milillo, J. S. Oliveira, Y. J. Lee, S. McKenna-Lewlor, D. Grassi, D. Heyner, A. S. Kozyrev, R. Peron, J. Helbert, S. Besse, S. de la Fuente, E. Montagnon, J. Zender, M. Volwerk, J-Y. Chaufray, J. A. Slavin, H. Krueger, A. Maturilli, T. Cornet, K. Iwai, Y. Miyoshi, M. Lucente, S. Massetti, C. Schmidt, C. Dong, F. Quarati, T. Hirai, A. Varsani, D. Belyaev, J. Zhong, E. K. J. Kilpua, B. V. Jackson, D. Odstrcil, F. Planschke, R. Vainio, R. Jarvinen, S. L. Ivanovski, A. Madar, G. Erdos, C. Plainaki, T. Alberti, S. Aizawa, J. Benkhoff, G. Murakami, E. Quemerais, H. Hiesinger, I. G. Mitrofanov, L. Iess, F. Santoli, S. Orsini, H. Lichtenegger, G. Laky, S. Barabash, R. Moissl, J. Huovelin, Y. Kasaba, Y. Saito, M. Kobayashi, and W. Baumjohann, BepiColombo science investigations during cruise and flybys at the Earth, Venus and Mercury, Space Science Reviews, in press, 2021

ROSETTA

Güttler, C., Mannel, T., Rotundi, A., Merouane, S., Fulle, M., Bockelée-Morvan, D., ... & Rinaldi, G. (2019). Synthesis of the morphological description of cometary dust at comet 67P/Churyumov-Gerasimenko. Astronomy & Astrophysics, 630, A24.

Lasue, J., Maroger, I., Botet, R., Garnier, P., Merouane, S., Mannel, T., ... & Bentley, M. S. (2019). Flattened loose particles from numerical simulations compared to particles collected by Rosetta. Astronomy & Astrophysics, 630, A28.

Hoang, M., Garnier, P., Gourlaouen, H., Lasue, J., Rème, H., Altwegg, K., ... & Wurz, P. (2019). Two years with comet 67P/Churyumov-Gerasimenko: H2O, CO2, and CO as seen by the ROSINA/RTOF instrument of Rosetta. Astronomy & Astrophysics, 630, A33.

Levasseur-Regourd, A. C., Renard, J. B., Hadamcik, E., Lasue, J., Bertini, I., & Fulle, M. (2019). Interpretation through experimental simulations of phase functions revealed by Rosetta in 67P/Churyumov-Gerasimenko dust coma. Astronomy & Astrophysics, 630, A20.

Levasseur-Regourd, A. C., Baruteau, C., Lasue, J., Milli, J., & Renard, J. B. (2020, September). Linear polarization as a tool to characterize interplanetary, cometary, and extrasolar dust particles. In Europlanet Science Congress 2020. Virtual Meeting (Vol. 14).

Levasseur-Regourd, A. C., Baruteau, C., Lasue, J., Milli, J., & Renard, J. B. (2020). Linking studies of tiny meteoroids, zodiacal dust, cometary dust and circumstellar disks. Planetary and Space Science, 186, 104896.

Hoang, M., Garnier, P., Lasue, J., Rème, H., Capria, M. T., Altwegg, K., ... & Rubin, M. (2020). Investigating the Rosetta/RTOF observations of comet 67P/Churyumov-Gerasimenko using a comet nucleus model: influence of dust mantle and trapped CO. Astronomy & Astrophysics, 638, A106.

Future Missions and instruments

Wiens, R. C., Wan, X., Lasue, J., & Maurice, S. (2020). Laser-induced breakdown spectroscopy in planetary science. In Laser-Induced Breakdown Spectroscopy (pp. 441-471). Elsevier.

Lasue, J.; Maurice, S.; Virmontois, C.; Bernardi, P.; Doressoundiram, A.; Carter, J.; Chevrel, S.; Dehouck, E.; Douté, S.; Flahaut, J.; Le Mouélic, S.; Pinet, P.; Quantin-Nataf, C., The REgolith Moon ExplOrer (ROMEO) Camera Science Case and Implementation, 51st Lunar and Planetary Science Conference (virtual), 16-20 March, 2020, Texas. LPI Contribution No. 2326, 2020, #1819

Meslin, P. Y.; He, H.; Kang, Z.; Wimmer-Schweingruber, R.; Sabroux, J. C.; Pineau, J. F.; Yamashita, N.; Sabot, B.; Pierre, S.; Blanc, M.; Roques, J. P.; Plotnikov, I.; Maurice, S.; Gasnault, O.; Amestoy, J.; Pinet, P.; Forni, O.; Lasue, J.; Guertin, A.; Métivier, V., Radon and Polonium as Tracers of Lunar Outgassing, Volatiles, and Dust: Going Back to the Moon?, 51st Lunar and Planetary Science Conference (virtual), held 16-20 March, 2020, Texas. LPI Contribution No. 2326, 2020, # 1741

Barucci Maria Antonietta, Reess Jean-Michel, Bernardi Pernelle, Doressoundiram Alain, Fornasier Sonia, et al., MIRS an Imaging spectrometer for the MMX mission, [Earth and Planetary Science Letters] Soumis (2020).

Italy 2020 Report

1. Team Project Report

During 2020, the Italian scientific community continued developing their initiatives related to exploration of the Moon, Martian Moons and Near Earth Asteroids, although the activities were partially affected by the COVID-19 global pandemic situation. Among other impacts, covid also forced us to reconfigure the 8th edition of the European Lunar Symposium - 2020 to an only virtual/ online edition. Thanks to the invaluable work of the Organizing Committees lead by the SCF_Lab of INFN-LNF and the great support of the SSERVI Central Office and Personnel, the European Lunar Symposium 2020 was indeed a success in terms of participation and sharing of ideas and results, as shown by the following facts:

- It was one of the first, and very few events, which, at the beginning of the pandemics emergency, was able to restructure itself to be remotely accessible to its participants.

- There were almost 500 registered participants, from 36 countries, with about 200 people simultaneously attending at any given time, covering the vast majority of time zones, and not counting the live feed streamed online.

- The scientific impact of the symposium was remarkable: 65 talks, 18 posters; all the conference material, including the video streams, is available online at https://els2020.arc.nasa.gov/ .

As further indication of the large interest in Moon Exploration initiatives among relevant international partners, in October 2020 Italy joined the group of partner countries in signing the Artemis Accords, which establish a practical set of principles to guide space exploration cooperation among nations participating in the agency's 21st century lunar exploration plans.

Hon. Riccardo Fraccaro, Undersecretary of State at the Presidency of the Italian Council of Ministers.

1.1. INFN-LNF and ASI-MLRO

The SCF_Lab of INFN-LNF has worked jointly with the Matera Laser Ranging Observatory (MLRO) of the Italian Space Agency-CGS (Space Geodesy Center), on the following achievements:

- The INFN and MLRO Teams have collaborated fruitfully since 2005 with the Univ. of Maryland (D. Currie P.I.) on the development of a next generation single, large diameter lunar laser retroreflector. U. of Maryland, with INFN as Co-P.I. group, has been selected by NASA in the Lunar Surface Instrument and Technology Payloads (LSITP) program for the launch of this co-developed next-gen retroreflector on a 2023 lunar flight of the Commercial Lunar Payload Services (CLPS) program.

- INFN and MLRO Teams have also participated in the study proposal of a Lunar Geophysics Network (LGN) for submission to the next “New Frontiers 5” AO. The LGN includes the next-gen retroreflector co-developed with U. of Maryland. In 2019, NASA approved a 1-year LGN Mission Concept Study, completed in 2020, in which INFN and U. Maryland participated [Reference: LGN].

- INFN and MLRO participated in several White Papers for NASA’s Artemis III mission to the south pole and for the Planetary Science Decadal Survey 2023-2032 of The National Academies of Sciences, USA.

- The INFN Team is strongly involved in ESA’s lunar program. The INFN flagship next-generation laser retroreflector (MoonLIGHT, Moon Laser Instrumentation for General relativity and Geophysics High accuracy Tests) has been selected by ESA for the development and delivery of a MoonLIGHT Pointing Actuator (MPAc) [ELS-2020] and for the launch, under ESA support, of MoonLIGHT + MPAc with a NASA launch in 2023.

- INFN participates in the ESA Lunar Science Team that is in charge of preparing a plan that would be used as the basis of scientific investigations and payloads for ESA’s European Large Logistics Lunar Lander (EL3).

- Moreover, some INFN researchers participate to the International Lunar Research Team, coordinated by ESA and CNSA and specifically in the working group on geophysics, cartography (reference frames) and test of general relativity with lunar laser retroreflectors (provided by INFN) and lunar laser ranging (provided by ASI-MLRO). The goals of this research team is the cooperation between European and Chinese scientific teams to support the missions of both agencies, enhance the overall scientific return and to prepare for an international lunar research station.

- INFN has delivered through ASI two microreflectors for Mars rover missions. One of these is installed on NASA’s Perseverance rover and was launched in July 2020 (landing in Feb 2021) [LaRA]. The 2nd will be launched with ESA’s ExoMars 2022 rover.

- Within the NASA CLPS program, INFN has agreed to launch two Mars microreflectors onboard the Intuitive Machines (IM) 2021 mission. They will be installed on the two Moon Racer micro-rovers provided to IM by Moon Mark (https://moonmark.space).

- The Italian (ASI-INFN) pico laser retroreflector (4.7 gr mass) is of interest for ESA’s Hera mission to the double asteroid Didymos, that will also be the subject of NASA’s DART mission. Hera was approved by the last EU-ESA Ministerial Council for launch in 2024, and has a laser ranging/altimetry instrument onboard.

- INFN is continuing to develop custom laser retroreflectors for Phobos and Deimos surface missions that are of interest to NASA and SSERVI for laser observations from Mars orbit. Currently, ASI is investigating a potential interest by JAXA for the MMX mission to Phobos, which has a laser ranging instrument onboard.

- Finally, in collaboration with SSERVI (B. Day) and JPL (E. Law’s group), INFN is working with success on the first observation of Apollo laser retroreflectors via solar “glints” (reflections) recorded by the Lunar Reconnaissance Orbiter Camera and selected with NASA’s Moon Trek Software [Glints-EPSC] [Glint-ELS].

1.2. INAF – Istituto Nazionale di Astrofisica

The Italian National Institute of Astrophysics - INAF team is deeply involved in the lunar exploration preparatory activities, especially as part of the ESA PROSPECT user group, being the instrument payload of the Roscosmos Luna 27 mission. The Italian science team is composed of a wide group of scientists, all of them involved or strongly interested in lunar science and exploration. The Prospect User Group members were selected by ESA to define and ensure the scientific requirements of PROSPECT, to consolidate PROSPECT science objectives, to ensure PROSPECT is operated effectively at the lunar surface and to increase the scientific return of the expected data. The main purpose of PROSPECT is to support the identification of potential resources on the Moon and to assess the utilization of those resources. Water and other volatiles found at the surface of the Moon could provide major potential assets for future exploration, with vital consumables for human explorers and as a source of oxygen for life support systems. Moreover, hydrogen and oxygen as can be extracted from lunar soil and used as fuel.

INAF-Astrophysical Observatory of Arcetri OAA is involved in the analysis of samples extracted by the ProSEED drill of the ESA PROSPECT package, investigating physico-chemical properties of volatiles and water in lunar samples. A dedicated test setup was used at INAF- OAA to investigate the adsorption and desorption of water on lunar regolith using a high-vacuum setup for temperature-programmed desorption (TPD). For this purpose, simulants (highland type or its individual mineral constituents) are used as a baseline to study the adsorption kinetics on a most representative particle surface. The outcome of this study was an empirical relation between desorption energy and temperature for water on lunar regolith that can be used to inform the simulation models.

The launch of Luna 27 has been recently delayed to 2025. Meanwhile, NASA started a discussion with ESA to have PROSPECT as an element in one of the next Artemis missions: the approval and the programmatic details are currently under discussion among the Agencies.

The INAF started in 2020 an initiative to survey the Italian lunar scientific community for the preparation of a “white paper” to collect the capabilities and interests of the national research groups, to promote the further development of existing expertise and of new initiatives.

INAF participated on the International Lunar Research Team, coordinated by ESA and CNSA, that has been closed during spring 2020. There will be a document that will resume the main activities and the interactions between the two communities.

INAF is also involved in OSIRIS-Rex mission for both laboratory support in data interpretation and sample return analysis. The team investigates thermal modification of mineral spectra in space simulated conditions with the aim of creating a spectroscopic database of mineral dust with different sizes in the wavelength range from visible to far infrared at different temperature. This kind of analysi s is carried out with the unique IR facility available in the lab which allows in the same experimental apparatus the collection of spectra from VIS to FIR wavelengths in a broad temperature range from cryogenic to high temperatures. The team is also involved in the study, both experimental and modelling, of the effects of grain size and different mineral composition on spectral features.

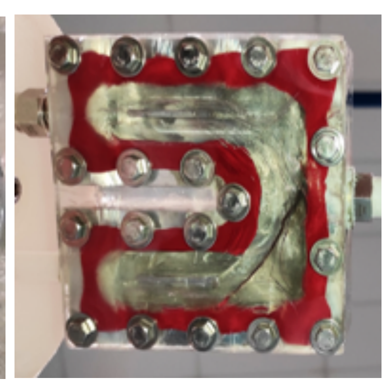
1.3. Politecnico di Milano

Politecnico di Milano is continuing to work on In-Situ Resources Utilization (ISRU) framework, with particular attention on water production from Moon regolith. The experimental plant in PoliMi labs has been finalized, functionally tested, and the process tests started being conducted in Q4 2020.

The possibility of extracting oxygen from regolith oxides with no feedstock melting, through a Carbothermal Reduction (CRB) process has been demonstrated and the expected yield in water production has been experimentally confirmed. Activities were carried on in synergy with ESA, ASI, and OHB company.

Fresh lunar simulant.

Used feedstock.



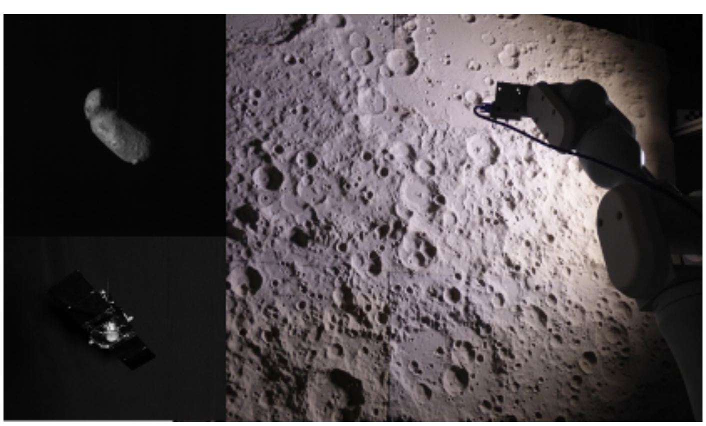
Condenser with produced water from oxides.

A correlated set of activities is related to Lunar South Pole soil simulant characterization in thermal vacuum conditions. In fact, reproducing a planetary soil simulant bed is a tough challenge, from the need of repeatable procedures to prepare the soil with desired physical properties, to the need to ensure its preservation during thermal-vacuum operations, and the task becomes even more complex with the presence of volatiles.

PoliMi is currently running a set of preparatory activities to characterize different soil components according to pressure and temperature variations. Politecnico di Milano is also part of the PROSPECT user group of ESA, with responsibility of the PROSEED - DRILL tool's science operations. Particular attention is given to modelling and verifying the thermal energy exchange process between the icy soil - sampled at the lunar poles – and the drilling tool to avoid any sublimation of the icy content the science is interested in.

In the area of ISRU for planetary manned missions, PoliMi-ASTRA is carrying on applied research in biomass growing in space for CO2 recycling and biomass production. In collaboration with the Cultifutura SME and ENEA group, PoliMi skills in modelling the biomass dynamics and synthetizing control laws for the key parameters to maximize either the biomass or the O2\CO2 recycling, were merged with the breadboards at ENEA to finalize a small prototype to be sent onboard one of the incoming lunar landers, for in-situ verification.

Politecnico di Milano, ASTRA Team, is also working on vision-based navigation and hazard avoidance for autonomous landing and proximity maneuvering; in particular, the team is still involved in the AIVIONICS ESA study to experimentally assess the effectiveness of artificial intelligence techniques when applied to image processing to perform autonomous navigation during



Experimental facility @Polimi for visual based relative GNC testing\ development.

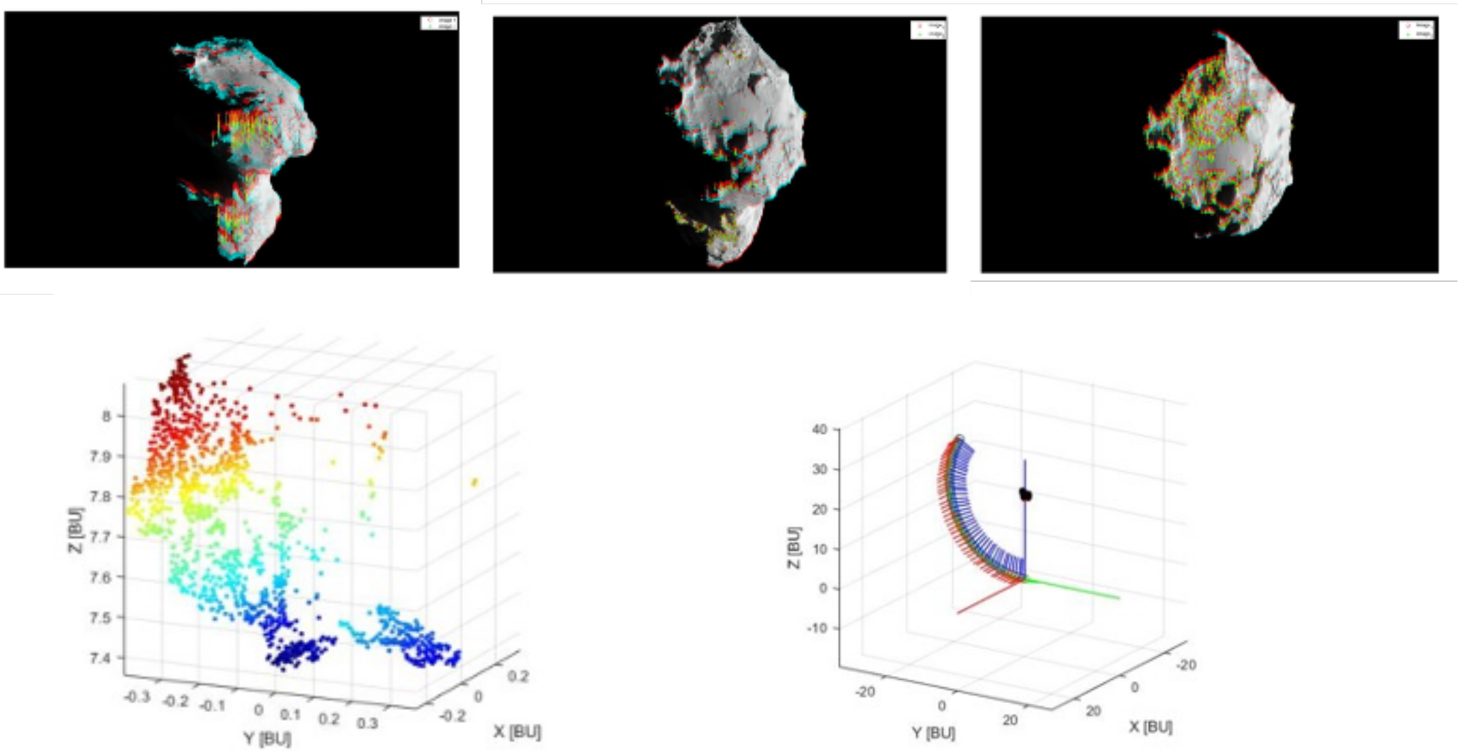
relative dynamics; a strong verification campaign with HIL is included in the study, leveraging the PoliMi in-house GNC experimental laboratory equipped with calibrated lunar surface diorama for landing and satellite mockups for proximity maneuvering.

For several years, Politecnico di Milano, ASTRA Team has been developing GNC techniques for non-keplerian trajectories with particular attention to the cis-lunar environment and proximity maneuvers, to support LOP-G related scenarios. In particular, PoliMi is in charge of supporting the rendezvous docking\undocking guidance definition for the Cis-lunar transfer Vehicle (CLTV), currently under preliminary design under an ESA contract led by TAS-I.

PoliMi-ASTRA is running 1 PhD research in collaboration with ESA Mission analysis division, focused on assessing the benefit of exploiting long duration missions in cis-lunar environment to promptly react to potentially hazardous Near-Earth asteroids or close passing comets on a collision trajectory with Earth. Missions in stable trajectories could perform a fast flyby or perform deviation actions for Planetary Defense reactions. Assessment involves all system engineering aspects towards actual feasibility.

Because of the strong expertise in chaotic dynamics in multi-attractor regimes, the ASTRA PoliMi team is also researching distributed\fractionated architectures for both scientific and servicing functionalities exploiting the most beneficial characteristics of non-keplerian orbits families in cis-lunar environment. In particular, constellations spread in the Moon-Earth volume are under investigation, to provide NAV-COMM services and to build up a very large baseline astrophysical observatory for high precision cosmic event localization; in collaboration with INAF-OAB, a new fractionated architecture is currently being investigated for an X-ray telescope with very large aperture and focal length. By properly combining the natural dynamics of the lunar surface– where the detector is supposed to be – with a proper non-keplerian orbit which hosts the mirror, both attitude and center of mass dynamics between detector and mirrors can be to synchronized as stationary.

The PoliMi ASTRA Team is deeply involved in small bodies related research, too. In particular, different areas can be identified: gravitational models for non-uniform mass distribution of target bodies; proximity maneuvering for scientific requirements satisfaction, trajectory definition, and GNC design with attention to image-based measurements. PoliMi-ASTRA was recently involved with



Example for AI supporting: image processing (top), mapping (bottom left) and trajectory reconstruction (bottom right).

ESA in assessing the chance to exploit the onboard HERA VIS camera to support, from main spacecraft, the relative navigation of its cubesats from detachment to Didymos system proximity; the team was also involved in AIM-ESA mission phase A to define trajectories and operations to both get to the Didymos binary and move in the gravity multi-regime environment; it is currently involved in the ASI-financed LICIA cubesat mission, for the cubesat trajectory, GNC and attitude control from the release to end of life, and to maximize the scientific return.

PoliMi -ASTRA, thanks to its competence in non-keplerian dynamics, is currently investigating how to exploit the multibody Martian moons environment to cleverly design trajectories to build the NAV-COMM constellation to service incoming missions to Mars, under an ESA contract led by TAS-I.

In collaboration with INAF-OAA the concept for a cubesat size lander robotics for in-situ sample collection and investigation is under development, targeting Deimos for astrobiology mapping.

1.4. International Research School of Planetary Sciences

The International Research School of Planetary Sciences (IRSPS) is a non-profit Organization devoted to research and post-graduate education. The School is an emanation of the Universita' d'Annunzio and is hosted by Dipartimento di Ingegneria e Geologia (InGeo). Planetary research mainly deals with the sub-disciplines of geology, geochemistry, geophysics, petrology, and exobiology. However, the IRSPS is not limited to these subjects and it welcomes scientific contributions from any field of planetary sciences including the Earth, which is also seen as a planet. The educational programs are not restricted to those fields and will cover the entire spectrum of planetary disciplines by joint ventures and collaborations with other international institutions.

IRSPS is currently working for Thales Alenia Space-Italia and ESA on the selection of the landing sites for the next ExoMars mission. The analysis is mainly focused on the physical and geological characteristics of the area, evaluating risk, and defining hazards in geographical terms.

IRSPS personnel are also participating in the scientific activity of MARSIS on Mars Express, SharRad on MRO, Dawn mission, BepiColombo and JUICE missions.

IRSPS, jointly with the Faculté de Sciences of the Université Cadi Ayyad (Marrakech Morocco), with some difficulties induced by the pandemic situation, continued to conduct preparations for new tests at the Ibn Battuta Centre (Morocco) for exploration and field activities on Mars and Lunar analogues certified sites. Recent tests on the characterization of the responses of the ExoMars radar altimetry and DREAMS instrument, as well as a test campaign on the Sherpa TT, DFKI 2nd generation rover, have been carried out.

In 2020 IRSPS participated in the NASA/SSERVI Analogs Focus Group teleconferences and confirms the interest in contributing to the virtual seminar series. IRSPS also presented, jointly with INAF, the paper “Perspectives for Radar Remote Sensing of the Moon” at the ELS 2020.
In December 2020 a representative of IRSPS was appointed as member of the ESA HRE-S strategy group for the Moon. It is also worth reporting IRSPS personnel activity on a nationally funded project dedicated to study the use of a Moon-based instrument for the detection of gravitational waves.

2. Public Engagement

Due to restrictions caused by the COVID-19 situation, the vast majority of 2020 outreach events were arranged by digital tools. Among the others, the Museo Civico di Rovereto has been particularly active with its YouTube and Facebook channels for virtual events involving the local public, with some in-person exceptions. One example is MCR’s involvement in the “International Observe the Moon Night 2020” event on 26th September 2020: at the Astronomical Observatory located in Monte Zugna, participants were involved in Moon observations by telescopes and in scientific seminars about moons of the Solar System.

ArgoMoon cubesat ProtoFlight Model.

3. Mission Involvement

The national missions for Solar System Exploration are essentially cubesat-based, as part of international initiatives. In particular, ArgoMoon and LICIACube will allow the Italian community to setup and validate

Poster of International Observe the Moon Night 2020.

Participants at observations session in Monte Zugna.

complete end-to-end space systems operating in the deep space environment, paving the way for future opportunities for cooperation and national initiatives.

"Argomoon" is a 6U cubesat selected in 2016 by NASA HQ Exploration Systems Mission Directorate (ESMD) as a Secondary Payload for the Artemis 1 mission of the Space Launch System (SLS), the heavy-lift launch vehicle designed to allow space exploration beyond Low-Earth Orbit. The first part of the ArgoMoon mission will take significant photographs of the launcher, while in the following six months, the satellite will orbit around the Earth with an apogee close to lunar orbit, to collect pictures of the lunar surfaces.

During the 2020, the ArgoMoon ProtoFlight Model has been fully integrated and completed the vast majority of the qualification/acceptance test campaign, with delivery to NASA MSFC expected in March 2021.

ASI is also completing the development of "LICIACube - Light Italian Cubesat for Imaging of Asteroids," a 6U cubesat that will participate in the NASA Double Asteroid Redirection Test (DART) mission to the secondary asteroid of the binary system Didymos, in order to test orbit deflection methods for Planetary Defense purposes. LICIACube will be launched as piggyback of DART spacecraft, then will be separated in proximity of the target and will perform an autonomous fly-by of the binary Didymos system during the final part of the DART mission, collecting pictures of the asteroid surface and of the generated ejecta plume.

During 2020, the design of the cubesat was completed and all the subsystems were developed and procured. Mission design and readiness has been refined jointly with the APL team, and shipment to the USA for integration onto DART is planned for May 2021.

Another Italian initiative currently supported by ESA, the Lunar Meteoroid Impacts Observer (LUMIO), is one of four projects selected within ESA's SysNova Competition No. 4 "Lunar CubeSats for Exploration" (LUCE). The goal of the competition was to perform multiple Phase 0 studies for nanosatellites (CubeSats) to conduct scientific and technology demonstrations when deployed by a mother ship around the Moon. LUMIO is a mission to observe, quantify, and characterize the meteoroid impacts by detecting the impact flashes on the lunar far-side. This will complement the knowledge gathered by Earth-based observations of the lunar nearside, thus synthesizing global information on the lunar meteoroid environment. LUMIO was co-winner of the LUCE competition, and as such it has been assessed by a team of ESA experts in a series of dedicated sessions at the Concurrent Design Facility (CDF) at ESA/ESTEC. The mission is currently facing the Preliminary Requirements Review, which concludes the Phase A study conducted under ESA contract and with the support of ASI. Politecnico di Milano is the Prime Contractor and principal investigator of the Phase A study for LUMIO.

REFERENCES

C. Neal et al, The Lunar Geophysical Network Landings Sites Science Rationale, submitted to Planetary Science (2020).

Rubino, L. et al, Motor Control System of Laser Retroreflectors for the return to the Moon, 8th European Lunar Symposium, https://youtu.be/ffSg9hzf7w8 (2020).

NASA's new Mars rover is ready for space lasers, NASA News 29 Sep. 2020, https://mars.nasa.gov/news/8762/nasas-new-mars-rover-is-ready-for-space-lasers/ (2020).

[ArtIII] Lunar Laser Ranging on Artemis III: Operation and Science Goals, J. Williams et al, paper n. 2073, submitted to NASA's Call for Artemis Science White Papers (2020).

LROC candidate images with solar glints off Lunar Laser Retroreflectors: A dedicated tool of NASA's Moon Trek, C. Rossi et al, European Planetary Science Conf., https://doi.org/10.5194/epsc2020-614 (2020).

E. Law, G. Chang, N. Gallegos, S. Malhotra, S. Casini, B. Day, D. Currie, S. Dell'Agnello (2020) Applications and planning for lunar laser retroreflector studies, 8th European Lunar Symposium (2020).

Dotto, E., et al.: LICIACube - the Light Italian Cubesat for Imaging of Asteroids: in support of the NASA DART mission towards asteroid (65803) Didymos, Plan. Space Sci., 2020, accepted.

A. Capannolo et al., Challenges in LICIA Cubesat Trajectory Design to Support DART Mission Science, Acta Astronautica, 2020, accepted.

M. Piccinin, M. Lavagna, Deep reinforcement learning approach for small bodies shape reconstruction enhancement, AIAA Scitech 2020 Forum

S. Silvestrini, A. Capannolo, A., M. Piccinin, M. Lavagna, J.G. Fernandez, Centralized autonomous relative navigation of multiple spacecraft around small bodies, AIAA Scitech 2020 Forum

M. Piccinin, G. Zanotti, S. Silvestrini, A. Capannolo, A. Pasquale, M. Lavagna, Cubesat exploration missions to binary asteroids: on board autonomy and intelligent imaging towards science return enhancement , proceedings of 2020 AAS/AIAA Astrodynamics Specialist virtual Lake Tahoe conference, paper no.AAS 20-754, August 9-13, 2020

M. Lavagna, S. di Marco, L. Colaninno, P. Minacapilli, J. Petrucci, A. Pasquale, Reachability maps generation for opportunistic targets interception from Cis-lunar orbits, proceedings of 2020 AAS/AIAA Astrodynamics Specialist virtual Lake Tahoe conference,paper no.AAS 20-753, August 9-13, 2020

G. Zanotti, M. Lavagna, Science opportunities in the Didymos binary: the role of post-impact ejecta long-term dynamics in the proximity operations definition, paper no.A3.4-A.5, IAC2020, Cyber Space Edition 12-14 Oct 2020

A. Capannolo, M. Lavagna, Minimum Cost Relative Dynamics in Cislunar Environment, paper no.C1.6-6, IAC2020, Cyber Space Edition 12-14 Oct 2020

S. Silvestrini, P. Lunghi, M. Piccinin, G. Zanotti, M. Lavagna, Artificial Intelligence Techniques in Autonomous Vision-Based Navigation System for Lunar Landing, paper no. C1.2-1 IAC2020, Cyber Space Edition 12-14 Oct 2020.

SSERVI TEAM PUBLICATIONS IN 2020

The following list of publications was compiled from all SSERVI teams for 2020, bringing the total for year 1 through year 7 to 1028.

1. Arredondo, A., Lorenzi, V., Pinilla-Alonso, N., Campins, H., Malfavon, A., de León, J., & Morate, D. (2020). Near-infrared spectroscopy of the Klio primitive inner-belt asteroid family. Icarus, 335, 113427. doi: 10.1016/j.icarus.2019.113427

2. Atkinson, J., Prasad, M., Abbud-Madrid, A., Dreyer, C. B. (2020). Penetration and relaxation behavior of JSC-1A lunar regolith simulant under cryogenic conditions. Icarus, 346. doi: 10.1016/j.icarus.2020.113812

3. Avdellidou, C., Didonna, A., Schultz, C., Harthong, B., Price, M. C., Peyroux, R., ... & Cole, M. (2020). Very weak carbonaceous asteroid simulants I: Mechanical properties and response to hypervelocity impacts. Icarus, 341, 113648. doi: 10.1016/j.icarus.2020.113648

4. Barucci, M. A., Hasselmann, P. H., Praet, A., Fulchignoni, M., Deshapriya, J. D. P., Fornasier, S., ... & Lauretta, D. S. (2020). OSIRIS-REx spectral analysis of (101955) Bennu by multivariate statistics. Astronomy & Astrophysics, 637, L4. doi: 10.1051/0004-6361/202038144

5. Bassett N., Rapetti D., Burns J.O., Tauscher K., MacDowall R. (2020). Characterizing the radio quiet region behind the lunar farside for low radio frequency experiments. Advances in Space Research, 66 (6), 1265-1275. doi: 10.1016/j.asr.2020.05.050

6. Bretzfelder J. M., Klima R. L., Greenhagen B. T., Buczkowski D. L., Petro N. E., Day M. (2020). Identification of potential mantle rocks around the lunar Imbrium Basin. Geophysical Research Letters, 47, e2020GL090334. doi: 10.1029/2020GL090334

7. Burbine T. H., Greenwood R. C. (2020). Exploring the Bimodal Solar System via Sample Return from the Main Asteroid Belt: The Case for Revisiting Ceres. Space Science Reviews, 216 (59). doi: 10.1007/s11214-020-00671-0

8. Burns J. O. (2020). Transformative science from the lunar farside: observations of the dark ages and exoplanetary systems at low radio frequencies. Philosophical Transactions of the Royal Society A, 379 (2188). doi: 10.1098/rsta.2019.0564

9. Cannon K. M., Britt D. T., (2020). Accessibility data set for large permanent cold traps at the lunar poles. Earth and Space Science, 7, e2020EA001291. doi: 10.1029/2020EA001291

10. Cannon K. M., Britt D. T., (2020). A geologic model for lunar ice deposits at mining scales. Icarus, 347, 113778. doi: 10.1016/j.icarus.2020.113778

11. Cannon K. M., Deutsch A. N., Head J. W., Britt D. T. (2020). Stratigraphy of ice and ejecta deposits at the lunar poles. Geophysical Research Letters, 47, e2020GL088920. doi: 10.1029/2020GL088920

12. Cao, X., Halekas, J. S., Chu, F., Kistler, M., Poppe, A. R., & Glassmeier, K. H. (2020). Plasma Convection in the Terrestrial Magnetotail Lobes Measured Near the Moon's Orbit. Geophysical Research Letters, 47(20), e2020GL090217. doi: 10.1029/2020GL090217

13. Cao X., Halekas J., Poppe A., Chu F., Glassmeier K. H. (2020). The Acceleration of Lunar Ions by Magnetic Forces in the Terrestrial Magnetotail Lobes. Journal of Geophysical Research: Space Physics, 125. 10.1029/2020JA027829

14. Carroll A., Hood N., Mike R., Wang X., Hsu H.-W., Horanyi M. (2020). Laboratory measurements of initial launch velocities of electrostatically lofted dust on airless planetary bodies. Icarus, 352. doi: 10.1016/j.icarus.2020.113972

15. Castillo-Rogez, J., Neveu, M., McSween, H. Y., Fu, R. R., Toplis, M. J., & Prettyman, T. (2018). Insights into Ceres's evolution from surface composition. Meteoritics & Planetary Science, 53(9), 1820-1843. doi: 10.1111/maps.13181

16. Chen, X., Fan, X., Li, L., Zhang, N., Niu, Z., Guo, T., ... & Zeng, C. (2020). Moiré engineering of electronic phenomena in correlated oxides. Nature Physics, 16(6), 631-635. doi: 10.1038/s41567-020-0865-1

17. Chen, X., Liu, X., Guo, X., Chen, S., Hu, H., Nikulina, E., ... & You, G. (2020). The near-field imaging of extreme subwavelength metal structures. ACS Photonics, 7(3), 687-694. doi: 10.1029/2019EA000915

18. Cloutis, E. A., Hewson, D., Applin, D. M., Mann, J. P., & Mertzman, S. A. (2018). Raman and reflectance spectroscopy of serpentinites and related hydrated silicates: effects of physical properties and observational parameters, and implications for detection and characterization on Mars. Planetary and Space Science, 159, 66-83. doi: 10.1016/j.pss.2018.04.016

19. De Prá, M. N., Pinilla-Alonso, N., Carvano, J., Licandro, J., Morate, D., Lorenzi, V., ... & Mothé-Diniz, T. (2020). A comparative analysis of the outer-belt primitive families. Astronomy & Astrophysics, 643, A102. doi: 10.1051/0004-6361

20. de Wet W., Slaba T., Rahmanifard F., Wilson J., Jordan A., Townsend L., Schwadron N., Spence H. (2020). CRaTER observations and permissible mission duration for human operations in deep space. Life Sciences in Space Research, 26. doi: 10.1016/j.lssr.2020.04.00

21. Deca, J., Hemingway, D. J., Divin, A., Lue, C., Poppe, A. R., Garrick-Bethell, I., ... & Horányi, M. (2020). Simulating the Reiner Gamma Swirl: The Long-Term Effect of Solar Wind Standoff. Journal of Geophysical Research: Planets, 125(5), e2019JE006219. doi: 10.1029/2019JE006219

22. Dhar B., Pollock J., Gloria J., Kaden W. E. (2020). TPD characterization of Al-OD-Si sites at the interface of bilayer Al0.42Si0.5802/Ru(0001) thin-films. Surface Science, 696, 121595. doi: 10.1016/j.susc.2020.121595

23. Domingue, D., Palmer, E., Gaskell, R., & Staid, M. (2018). Characterization of lunar surface within Tsiolkovsky crater: Photometric properties. Icarus, 312, 61-99. doi: 10.1016/j.icarus.2018.02.034

24. Farr B., Wang X., Goree J., Hahn I., Israelsson U., Horanyi M. (2020). Dust mitigation technology for lunar exploration utilizing an electron beam. Acta Astronautica, 177. doi: 10.1016/j.actaastro.2020.08.003

25. Fedorets, G., Granvik, M., Jones, R. L., Jurić, M., & Jedicke, R. (2020). Discovering Earth's transient moons with the Large Synoptic Survey Telescope. Icarus, 338, 113517. doi: 10.1016/j.icarus.2019.113517

26. Flynn, G. J., Durda, D. D., Molesky, M. J., May, B. A., Congram, S. N., Loftus, C. L., ... & Macke, R. J. (2019, April). Momentum transfer in hypervelocity cratering of meteorites and meteorite analogs: Implications for asteroid deflection. In Hypervelocity Impact Symposium (Vol. 883556, p. V001T04A001). American Society of Mechanical Engineers. doi: 10.1115/HVIS2019-028

27. Furlanetto, S. R. (2021). Quasi-equilibrium models of high-redshift disc galaxy evolution. Monthly Notices of the Royal Astronomical Society, 500(3), 3394-3412. doi: 10.1093/mnras/staa3451

28. Garrick-Bethell, I., Miljković, K., Hiesinger, H., van der Bogert, C. H., Laneuville, M., Shuster, D. L., & Korycansky, D. G. (2020). Troctolite 76535: A sample of the Moon's South Pole-Aitken basin. Icarus, 338, 113430. doi: 10.1016/j.icarus.2019.113430

29. Giguere T., Hawke B., Gillis-Davis J., Lemelin M., Boyce J., Trang D., Lawrence S., Stopar J., Campbell B., Gaddis L., Blewett D., Gustafson J., Peterson C., Runyon C. (2020). Volcanic Processes in the Gassendi Region of the Moon. JGR Planets. doi: 10.1029/2019JE006034

30. Goderis S., Yesiltas M., Pourkhorsandi H., Shirai N., Poudelet M., Leitl M., Yamaguchi A., Debaille V., Claeys P. (2020). A detailed record of the BELARE 2019-2020 meteorite recovery expedition on the Nansen Ice Field, East Antarctica. Antarctic Record. doi:10.15094/00016237

31. Greenwood, R. C., Burbine, T. H., & Franchi, I. A. (2020). Linking asteroids and meteorites to the primordial planetesimal population. Geochimica et Cosmochimica Acta, 277, 377-406. doi: 10.1016/j.gca.2020.02.004

32. Hanna, K. D., Schrader, D. L., Cloutis, E. A., Cody, G. D., King, A. J., McCoy, T. J., ... & Schofield, P. F. (2019). Spectral characterization of analog samples in anticipation of OSIRIS-REx's arrival at Bennu: A blind test study. Icarus, 319, 701-723. doi: 10.1016/j.icarus.2018.10.018

33. Hendrix, A. R., & Vilas, F. (2019). C-complex asteroids: UV-visible spectral characteristics and implications for space weathering effects. Geophysical Research Letters, 46(24), 14307-14317. doi: 10.1029/2019GL085883

34. Howard, S. K., Halekas, J. S., Farrell, W. M., McFadden, J. P., & Glassmeier, K. H. (2020). Solar Wind and Interplanetary Magnetic Field Influence on Ultralow Frequency Waves and Reflected Ions Near the Moon. Journal of Geophysical Research: Space Physics, 125(2), e2019JA027209. doi: 10.1029/2019JA027209

35. James D., Fontanese J., Munsat T., Horanyi M. (2020). Calibration methods of charge sensitive amplifiers at the Colorado dust accelerator. Review of Scientific Instruments, 91 (113301). doi: 10.1063/5.0020018

36. Johnson, J. R., Jaret, S. J., Glotch, T. D., Sims, M. (2020). Raman and Infrared Microspectroscopy of Experimentally Shocked Basalts. Journal of Geophysical Research: Planets, 125. doi: 10.1029/2019JE006240

37. Jones B. M., Aleksandrov A., Dyar M. D., Hibbitts,C. A., Orlando T. M. (2020). Investigation of water interactions with Apollo lunar regolith grains. Journal of Geophysical Research: Planets, 125 (6). doi: 10.1029/2019je006147

38. Jones, B. M., Sarantos, M., Orlando, T. M. (2020). A New In Situ Quasi-continuous Solar-wind Source of Molecular Water on Mercury. The Astrophysical Journal, 891. doi: 10.3847/2041-8213/ab6bda

39. Joy, K. H., Snape, J. F., Nemchin, A. A., Tartèse, R., Martin, D. M., Whitehouse, M. J., ... & Kring, D. A. (2020). Timing of geological events in the lunar highlands recorded in shocked zircon-bearing clasts from Apollo 16. Royal Society open science, 7(6), 200236. doi: 10.1098/rsos.200236

40. Joy, K. H., Tartèse, R., Messenger, S., Zolensky, M. E., Marrocchi, Y., Frank, D. R., & Kring, D. A. (2020). The isotopic composition of volatiles in the unique Bench Crater carbonaceous chondrite impactor found in the Apollo 12 regolith. Earth and Planetary Science Letters, 540, 116265. doi: 10.1016/j.epsl.2020.116265

41. Kaplan, H. H., Lauretta, D. S., Simon, A. A., Hamilton, V. E., DellaGiustina, D. N., Golish, D. R., ... & Enos, H. L. (2020). Bright carbonate veins on asteroid (101955) Bennu: Implications for aqueous alteration history. Science, 370(6517). doi: 10.1126/science.abc3557

42. Kaplan, H. H., Hamilton, V. E., Howell, E. S., Scott Anderson, F., Barrucci, M. A., Brucato, J., ... & Lauretta, D. S. (2020). Visible–near infrared spectral indices for mapping mineralogy and chemistry with OSIRIS-RE x. Meteoritics & Planetary Science, 55(4), 744-765. doi: 10.1111/maps.13461

43. Kenny G. G., Karlsson A., Schmieder M., Whitehouse M.J., Nemchin A.A., Bellucci J. J. (2020). Recrystallization and chemical changes in apatite in response to hypervelocity impact. Geology, 48(1), 19-23. doi: 10.1130/G46575.1

44. Klima R. L., Bretzfelder J. M., (2021). The Moon. Encyclopedia of Geology (Second Edition), Academic Press, 86-93. doi: 10.1016/B978-0-08-102908-4.00147-8

45. Landis, M. E., Byrne, S., Combe, J. P., Marchi, S., Castillo-Rogez, J., Sizemore, H. G., ... & Russell, C. T. (2019). Water vapor contribution to Ceres' exosphere from observed surface ice and postulated ice-exposing impacts. Journal of Geophysical Research: Planets, 124(1), 61-75. doi: 10.1029/2018JE005780

46. Landis, M. E., Byrne, S., Schörghofer, N., Schmidt, B. E., Hayne, P. O., Castillo-Rogez, J., ... & Russell, C. T. (2017). Conditions for sublimating water ice to supply Ceres' exosphere. Journal of Geophysical Research: Planets, 122(10), 1984-1995. doi: 10.1002/2017JE005335

47. Lawrence, D. J., Peplowski, P. N., Beck, A. W., Feldman, W. C., Prettyman, T. H., Russell, C. T., ... & Neesemann, A. (2018). Compositional variability on the surface of 1 Ceres revealed through GRaND measurements of high-energy gamma rays. Meteoritics & Planetary Science, 53(9), 1805-1819. doi: 10.1111/maps.13124

48. Le Corre, L., Sanchez, J. A., Reddy, V., Takir, D., Cloutis, E. A., Thirouin, A., ... & Tatsumi, E. (2018). Ground-based characterization of Hayabusa2 mission target asteroid 162173 Ryugu: constraining mineralogical composition in preparation for spacecraft operations. Monthly Notices of the Royal Astronomical Society, 475(1), 614-623. doi: 10.1093/mnras/stx3236

49. Lewin C. D., Howell E. S., Vervack Jr. R. J., Fernandez Y. R., Magri C., Marshall S. E., Crowell J. L., Hinkle M. L. (2020). Near-infrared Spectral Characterization of Solar-type Stars in the Northern Hemisphere. The Astronomical Journal, 160 (3). doi: 10.3847/1538-3881/aba0c0

50. Li S., Lucey P. G., Fraeman A. A., Poppe A. R., Sun V. Z., Hurley D. M., Schultz P. H. (2020). Science Advances, 6 (36), eaba1940. doi: 10.1126/sciadv.aba1940

51. Lisse, C. M., Meng, H. Y. A., Sitko, M. L., Morlok, A., Johnson, B. C., Jackson, A. P., ... & Britt, D. T. (2020). HD 145263: Spectral Observations of Silica Debris Disk Formation via Extreme Space Weathering. The Astrophysical Journal, 894(2), 116. doi: 10.3847/1538-4357/ab7b80

52. Lisse, C., Bauer, J., Cruikshank, D., Emery, J., Fernández, Y., Fernández-Valenzuela, E., ... & Woodward, C. (2020). Spitzer's Solar System studies of comets, centaurs and Kuiper belt objects. Nature Astronomy, 4(10), 930-939. doi: 10.1038/s41550-020-01219-6

53. Lowry V. C., Vokrouhlick√Ω D., Nesvorn√Ω D., Campins H. (2020). Clarissa Family Age from the Yarkovsky Effect Chronology. The Astronomical Journal, 160 (3). doi: 10.3847/1538-3881/aba4af

54. Marchi, S., Walker, R. J., & Canup, R. M. (2020). A compositionally heterogeneous martian mantle due to late accretion. Science advances, 6(7), eaay2338. doi:10.1126/sciadv.aay2338

55. Mebane, R. H., Mirocha, J., & Furlanetto, S. R. (2020). The effects of population III radiation backgrounds on the cosmological 21-cm signal. Monthly Notices of the Royal Astronomical Society, 493(1), 1217-1226. doi: 10.1093/mnras/staa280

56. Molaro J. L., Hergenrother C. W., Chesley S. R., Walsh K. J., Hanna R. D., Haberle C. W., et al. (2020). Thermal fatigue as a driving mechanism for activity on asteroid Bennu. Journal of Geophysical Research: Planets, 125, e2019JE006325. doi: 10.1029/2019

57. Mustard, J. F., and T. D. Glotch (2019), Chapter 2: Theory of Emittance and Reflectance Spectroscopy of Geologic Materials in the Visible and Infrared Regions. In: Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces (Editors: J.L. Bishop, J.F. Bell III, and J.E. Moersch) pp. 289-306; Cambridge University Press; ISBN 9781107186200; doi: 10.1017/9781316888872

58. Nenon Q., Poppe A. R. (2020). On the Long-term Weathering of Airless Body Surfaces by the Heavy Minor Ions of the Solar Wind: Inputs from Ion Observations and SRIM Simulations. The Planetary Science Journal, 1 (3). doi: 10.3847/PSJ/abbe0c

59. Nerem, R. R., & James, D. (2020). Charged Particle Pickup Tube Detector Used in Experimental Applications and Classroom Demonstrations. The Physics Teacher, 58(3), 200-203. doi:10.1119/1.5145417.

60. Nerem, R. R., & James, D. (2020). Charged Particle Pickup Tube Detector Used in Experimental Applications and Classroom Demonstrations. The Physics Teacher, 58(3), 200-203. doi:10.1119/1.5145417.

61. Pastrnak, A., Henriquez, A., & La Saponara, V. (2020). Parametric study for tensile properties of molded high-density polyethylene for applications in additive manufacturing and sustainable designs. Journal of Applied Polymer Science, 137(42), 49283. doi: 10.1002/app.49283

62. Piquette, M., James, D., & Horanyi, M. (2020). Calibration of polyvinylidene fluoride based dust detectors in response to varying grain density and incidence angle. Review of Scientific Instruments, 91(2), 023307. doi: 10.1063/1.5125448

63. Pohl, L., & Britt, D. T. (2020). Strengths of meteorites—An overview and analysis of available data. Meteoritics & Planetary Science, 55(4), 962-987. doi: 10.1111/maps.13449

64. Povinec, P. P., Sýkora, I., Macke, R. J., Tóth, J., Kornoš, L., & Porubčan, V. (2020). Radionuclides in Chassigny and Nakhla meteorites of Mars origin: Implications for their pre-atmospheric sizes and cosmic-ray exposure ages. Planetary and Space Science, 186, 104914. Doi: 10.1016/j.pss.2020.104914

65. Prem, P., Hurley, D. M., Goldstein, D. B., & Varghese, P. L. (2020). The Evolution of a Spacecraft-Generated Lunar Exosphere. Journal of Geophysical Research: Planets, 125(8), e2020JE006464.
66. doi: 10.1029/2020JE006464

67. Prettyman, T. H., Englert, P. A., Yamashita, N., & Landis, M. E. (2019). Neutron, gamma-ray, and X-ray spectroscopy of planetary bodies. Remote Compositional Analysis: Techniques for Understanding Spectroscopy, 588-603. doi: 10.1017/9781316888872.032

68. Prettyman, T. H., Yamashita, N., Ammannito, E., Ehlmann, B. L., McSween, H. Y., Mittlefehldt, D. W., ... & Russell, C. T. (2019). Elemental composition and mineralogy of Vesta and Ceres: Distribution and origins of hydrogen-bearing species. Icarus, 318, 42-55. doi: 10.1016/j.icarus.2018.04.032

69. Rahmanifard F., de Wet W., Schwadron N., Owens M., Jordan A., Wilson J., Joyce C., Spence H., Smith C., Townsend L. (2020). Galactic Cosmic Radiation in the Interplanetary Space Through a Modern Secular Minimum. Space Weather. doi: 10.1029/2019SW002428

70. Rasca A. P., Fatemi S., Farrell W. M., Poppe A. R., Zheng Y. (2020). A Double Disturbed Lunar Plasma Wake. Journal of Geophysical Research: Space Physics, 125, e2020JA028789. doi: 10.1029/2020JA028789

71. Rasmussen, C., Stockli, D. F., Erickson, T. M., & Schmieder, M. (2020). Spatial U-Pb age distribution in shock-recrystallized zircon–A case study from the Rochechouart impact structure, France. Geochimica et Cosmochimica Acta, 273, 313-330. doi: 10.1016/j.gca.2020.01.017

72. Rhodes D., Farrell W., McLain J. (2020). Tribocharging and electrical grounding of a drill in shadowed regions of the

Moon. Advances in Space Research, 66. 10.1016/j.asr.2020.05.005 doi: 10.1016/j.asr.2020.05.005

73. Rhodes, D. J., & Farrell, W. M. (2020). Plasma expansion towards an electrically insulated surface. Journal of Plasma Physics, 86(2). doi:10.1017/S0022377820000148

74. Rhodes, D. J., Farrell, W. M. (2020). Mapping the Predicted Solar Wind Hydrogen Flux in Lunar South Pole Craters. The Planetary Science Journal, 1. doi: 10.3847/PSJ/ab8939

75. Ruzicka, A. M., Friedrich, J. M., Hutson, M. L., Strasser, J. W., Macke, R. J., Rivers, M. L., ... & Pugh, R. N. (2020). Shock compaction heating and collisional processes in the production of type 3 ordinary chondrites: Lessons from the (nearly) unique L3 chondrite melt breccia Northwest Africa 8709. Meteoritics & Planetary Science, 55(9), 2117-2140. doi: 10.1111/maps.13567

76. Sánchez, P., & Scheeres, D. J. (2020). Cohesive regolith on fast rotating asteroids. Icarus, 338, 113443. doi: 10.1016/j.icarus.2019.113443

77. Samaniego, J. I., Yeo, L. H., & Wang, X. (2020). A Double Hemispherical Probe for Characterizing and Minimizing the Self-Wake Effects on Probe Measurements. Journal of Geophysical Research: Space Physics, 125(10), e2020JA028508. doi: 10.1029/2020JA028508

78. Sarantos M., Tsavachidis S. (2020). The boundary of alkali surface boundary exospheres of Mercury and the Moon. Geophysical Research Letters, 47, e2020GL088930. doi: 10.1029/2020GL088930

79. Sargeant, H. M., Bickel, V. T., Honniball, C. I., Martinez, S. N., Rogaski, A., Bell, S. K., ... & Kring, D. A. (2020). Using boulder tracks as a tool to understand the bearing capacity of permanently shadowed regions of the moon. Journal of Geophysical Research: Planets, 125(2), e2019JE006157. doi: 10.1029/2019JE006157

80. Schaible M. J., Rosenberg R. A., Kundu S., Orlando T. M. (2020). Electron Spin-Polarization Dependent Damage to Chiral Amino Acid l-Histidine. The Journal of Physical Chemistry Letters, 11 (23), 10182-10187. doi: 10.1021/acs.jpclett.0c02855

81. Scheeres, D. J., French, A. S., Tricarico, P., Chesley, S. R., Takahashi, Y., Farnocchia, D., ... & Lauretta, D. S. (2020). Heterogeneous mass distribution of the rubble-pile asteroid (101955) Bennu. Science advances, 6(41), eabc3350. doi: 10.1126/sciadv.abc3350

82. Schieber, G. L., Jones, B., Orlando, T. M., & Loutzenhiser, P. G. (2019). Advection diffusion model for gas transport within a packed bed of JSC-1A regolith simulant. Acta Astronautica, 169:32-39. doi: 10.1016/j.actaastro.2019.12.031.

83. Schleicher, L. S., Watters, T. R., Martin, A. J., & Banks, M. E. (2019). Wrinkle ridges on Mercury and the Moon within and outside of mascons. Icarus, 331, 226-237. Doi: 10.1016/j.icarus.2019.04.013

84. Schmieder M. and Kring D. A. (2020). Earth's Impact Events Through Geologic Time: A List of Recommended Ages for Terrestrial Impact Structures and Deposits. Astrobiology, 20(1), 91-141. doi: 10.1089/ast.2019.2085

85. Schörghofer, N., & Hsieh, H. H. (2018). Ice loss from the interior of small airless bodies according to an idealized model. Journal of Geophysical Research: Planets, 123(9), 2322-2335. doi: 10.1029/2018JE005568

86. Seibers, Z. D., Brim, E., Lee Pittelli, S., Beltran, E., Shofner, M. L., & Reynolds, J. R. (2020). Readily Dispersible Chemically Functionalized Reduced Graphene Oxide Nanosheets for Solution-Processable Electrodes and Conductive Coatings. ACS Applied Nano Materials, 3(11), 11455-11464. doi: 10.1021/acsanm.0c02539

87. Seibers, Z., Orr, M., Collier, G. S., Henriquez, A., Gabel, M., Shofner, M. L., ... & Reynolds, J. (2020). Chemically Functionalized Reduced Graphene Oxide as Additives in Polyethylene Composites for Space Applications. Polymer

Engineering & Science, 60(1). doi: 10.1002/pen.25262

88. Semenenko V., Liu M., Perebeinos V. (2020). Scattering of Quasistatic Plasmons From One-Dimensional Junctions of Graphene: Transfer Matrices, Fresnel Relations, and Nonlocality. Phys. Rev. Applied, 14 (2), 024049. doi: 10.1103/PhysRevApplied.14.024049

89. Semenov, V. A., Kravtsov, A. V., & Gnedin, N. Y. (2018). How galaxies form stars: the connection between local and global star formation in galaxy simulations. The Astrophysical Journal, 861(1), 4. doi: 10.3847/1538-4357/aa932f

90. Shaosui X., Poppe A., Halekas J., Harada Y. (2020). Reflected Protons in the Lunar Wake and Their Effects on Wake Potentials. Journal of Geophysical Research: Space Physics, 125. doi: 10.1029/2020JA028154

91. Simon, A. A., Kaplan, H. H., Hamilton, V. E., Lauretta, D. S., Campins, H., Emery, J. P., ... & Bennett, C. A. (2020). Widespread carbon-bearing materials on near-Earth asteroid (101955) Bennu. Science, 370(6517). doi: 10.1126/science.abc3522

92. Sims, M., Jaret, S. J., Johnson, J. R., Whitaker, M. L., & Glotch, T. D. (2020). Unconventional high-pressure Raman spectroscopy study of kinetic and peak pressure effects in plagioclase feldspars. Physics and Chemistry of Minerals, 47(2), 12. Doi: 10.1007/s00269-020-01080-z

93. Sizemore, H. G., Platz, T., Schorghofer, N., Prettyman, T. H., De Sanctis, M. C., Crown, D. A., ... & Raymond, C. A. (2017). Pitted terrains on (1) Ceres and implications for shallow subsurface volatile distribution. Geophysical research letters, 44(13), 6570-6578. doi: 10.1002/2017GL073970

94. Sizemore, H. G., Schmidt, B. E., Buczkowski, D. A., Sori, M. M., Castillo-Rogez, J. C., Berman, D. C., ... & Raymond, C. A. (2019). A global inventory of ice-related morphological features on dwarf planet Ceres: Implications for the evolution and current state of the cryosphere. Journal of Geophysical Research: Planets, 124(7), 1650-1689. doi: 10.1029/2018JE005699

95. Stamenković, V., Beegle, L. W., Zacny, K., Arumugam, D. D., Baglioni, P., Barba, N., ... & Woolley, R. (2019). The next frontier for planetary and human exploration. Nature Astronomy, 3(2), 116-120. doi: 10.1038/s41550-019-0722-2

96. Sutton, S. R., A. Lanzirotti, M. Newville, M. D. Dyar, and J. Delaney (2020), Oxybarometry and valence quantification based on microscale X-ray absorption fine structure (XAFS) spectroscopy of multivalent elements, Chemical Geology, 531, 119305, doi:10.1016/j.chemgeo.2019.119305

97. Szalay, J. R., Pokorný, P., & Horányi, M. (2020). Hyperbolic Meteoroids Impacting the Moon. The Astrophysical Journal Letters, 890(1), L11. doi: 10.3847/2041-8213/ab7195

98. Tauscher K., Rapetti D., Burns J. O. (2020). Formulating and Critically Examining the Assumptions of Global 21 cm Signal Analyses: How to Avoid the False Troughs That Can Appear in Single-spectrum Fits. The Astrophysical Journal, 897 (2). doi: 10.3847/153

99. Trapp, A. C., & Furlanetto, S. R. (2020). A flexible analytic model of cosmic variance in the first billion years. Monthly Notices of the Royal Astronomical Society, 499(2), 2401-2415. doi: 10.1093/mnras/staa2828

100. Trilling, D. E., Lisse, C., Cruikshank, D. P., Emery, J. P., Fernández, Y., Fletcher, L. N., ... & Verbiscer, A. (2020). Spitzer's Solar System studies of asteroids, planets and the zodiacal cloud. Nature Astronomy, 4(10), 940-946. doi: 10.1038/s41550-020-01221-y

101. Vail O., Hankinson J., Berger C., de Heer W., Jiang Z. (2020). 1/f Noise in epitaxial sidewall graphene nanoribbons. Applied Physics Letters, 117. doi: 10.1063/5.0020926

102. Venditti F. C. F., Marchi L. O., Misra A. K., Sanchez D. M., Prado A. F. B. A. (2020). Dynamics of tethered asteroid systems to support planetary defense. The European Physical Journal Special Topics, 229, 1463-1477. doi: 10.1140/epjst/e2020-900183-y

103. Wang, Z., Wu, Y., Blewett, D. T., Cloutis, E. A., Zheng, Y., & Chen, J. (2017). Submicroscopic metallic iron in lunar soils estimated from the in situ spectra of the Chang'E-3 mission. Geophysical Research Letters, 44(8), 3485-3492. doi: 10.1002/2017GL072652

104. Williams, N. R., Bell III, J. F., Watters, T. R., Banks, M. E., Daud, K., & French, R. A. (2019). Evidence for recent and ancient faulting at Mare Frigoris and implications for lunar tectonic evolution. Icarus, 326, 151-161. Doi: 10.1016/j.icarus.2019.03.002

105. Wilson, J. K., Spence, H. E., Schwadron, N. A., Case, A. W., Looper, M. D., Jordan, A. P., et al. (2020). Precise detections of solar particle events and a new view of the moon. Geophysical Research Letters, 47, e2019GL085522. doi:10.1029/2019

106. Ye, C., Rucks, M. J., Arnold, J. A., & Glotch, T. D. (2019). Mid-Infrared Optical Constants of Labradorite, a Triclinic Plagioclase Mineral. Earth and Space Science, 6(12), 2410-2422. doi:10.1029/2019EA000915

107. Yesiltas, M., Kaya, M., Glotch, T. D., Brunetto, R., Maturilli, A., Helbert, J., & Ozel, M. E. (2020). Biconical reflectance, micro-Raman, and nano-FTIR spectroscopy of the Didim (H3-5) meteorite: Chemical content and molecular variations. Meteoritics & Planetary Science, 55(11), 2404-2421. doi: 10.1111/maps.13585

108. Zhu, C., Góbi, S., Abplanalp, M. J., Frigge, R., Gillis-Davis, J. J., Dominguez, G., ... & Kaiser, R. I. (2020). Regenerative water sources on surfaces of airless bodies. Nature Astronomy, 4(1), 45-52. doi:10.1038/s41550-41019-40900-41552